SUPERCONDUCTIVITY WS 15-16

Monday 10:00-11:30

SR Exp. physics II

Prof. Paul H.M. van Loosdrecht

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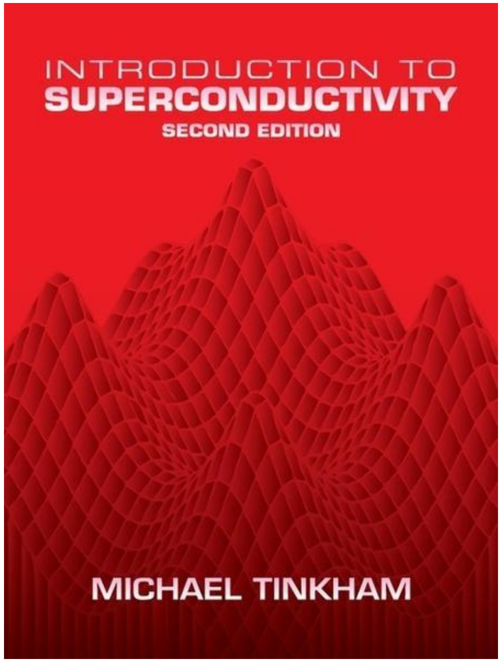
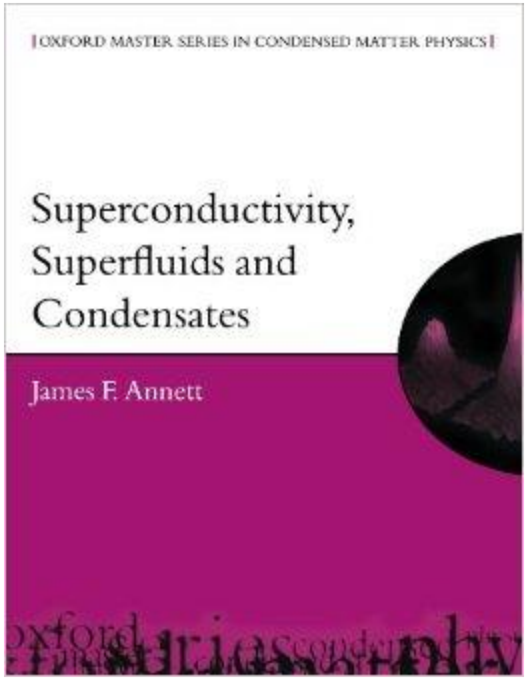
www.loosdrecht.net

Literature superconductivity


INTRODUCTION TO
SUPERCONDUCTIVITY
SECOND EDITION

MICHAEL TINKHAM


OXFORD MASTER SERIES IN CONDENSED MATTER PHYSICS

Superconductivity, Superfluids and Condensates

James F. Annett

Literature superconductivity

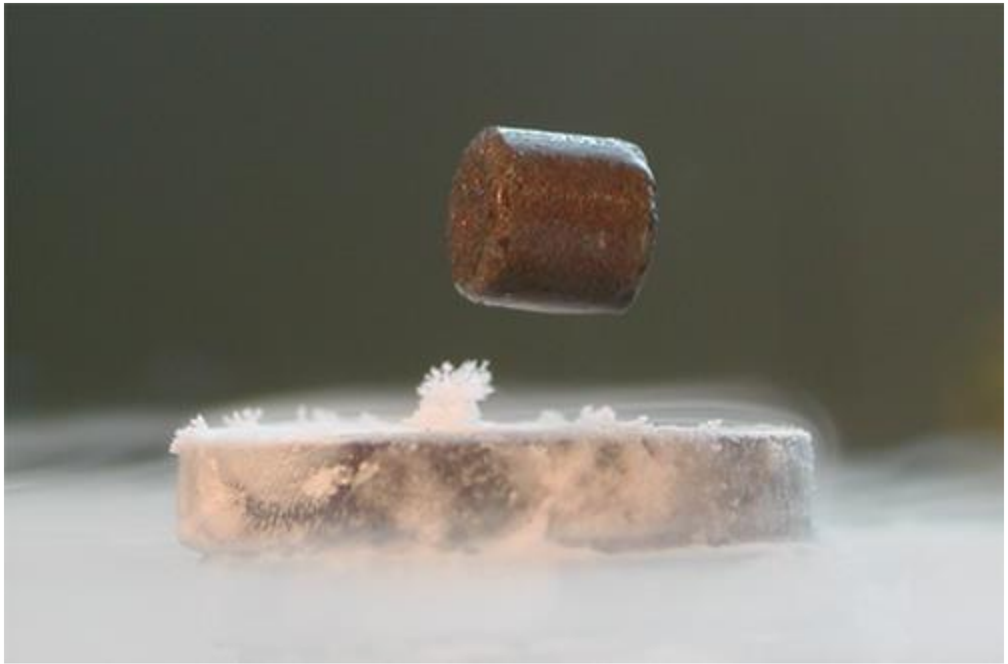
- M. Tinkham, Introduction to superconductivity (McGraw-Hill, 1996)
- J.F. Arnett, Superconductivity, superfluids, and condensates (Oxford Master series, 2004)
- J.R. Waldram, Superconductivity of metals and cuprates (IoP, 1996)
- S.J. Blundell, Superconductivity: A very short introduction (Oxford, 2009)
- Many others…

Further:

- Condensed matter physics
- Quantum mechanics
- Statistical physics/thermodynamics

Preliminary content

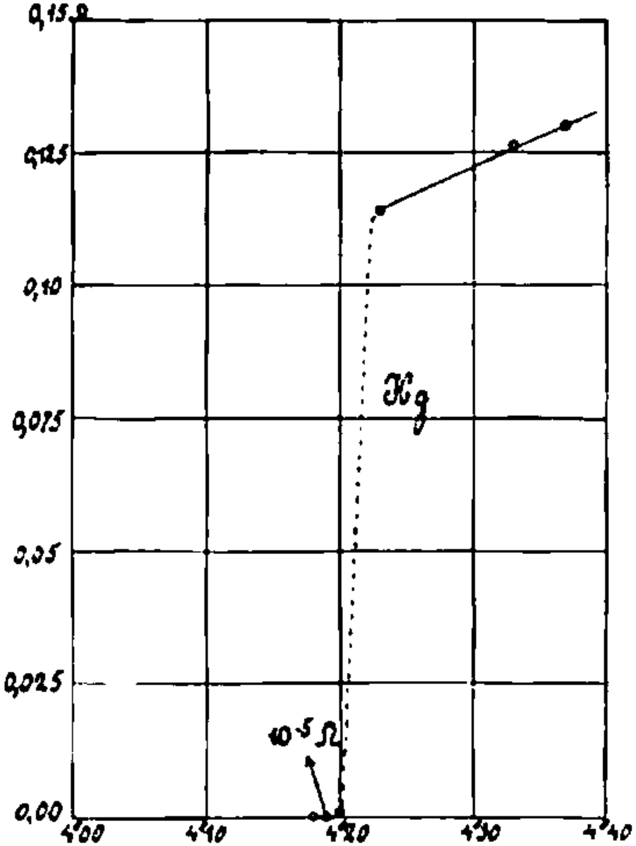
1 Introduction, historical overview
2 Basic properties
3 Materials and experimental aspects
4 BCS theory
5 Beyond BCS



Superconductivity

Gillis Holst

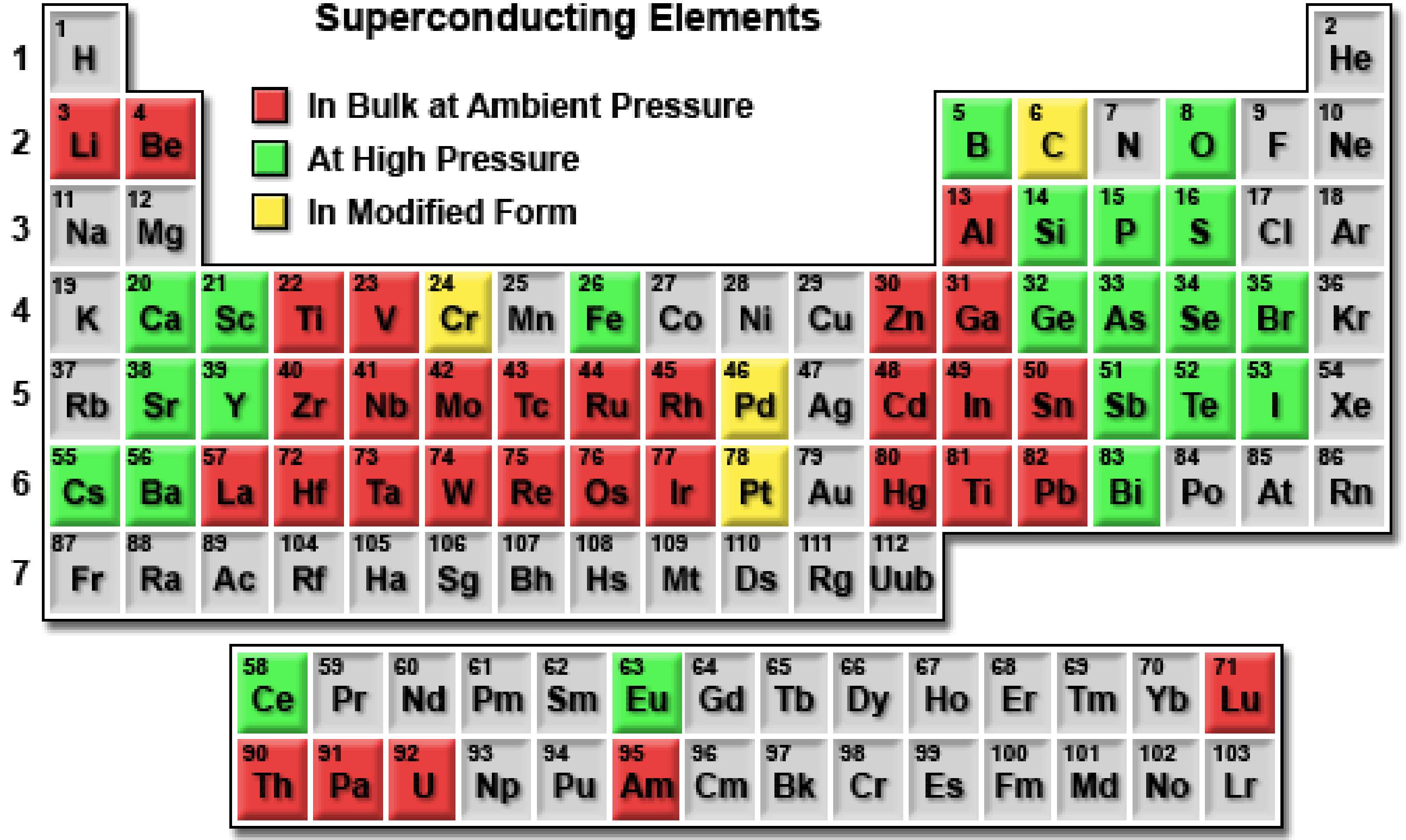
Heike Kamerlingh Onnes



1908 Liquid Helium
1911 Superconductivity

1913 Nobel Prize

Superconducting elements



Superconducting Elements

🟥 In Bulk at Ambient Pressure
🟩 At High Pressure
🟨 In Modified Form

1	1 H																	2 He
2	🟥 3 Li	🟥 4 Be											🟩 5 B	🟨 6 C	7 N	🟩 8 O	9 F	10 Ne
3	11 Na	12 Mg											🟥 13 Al	🟩 14 Si	🟩 15 P	🟩 16 S	17 Cl	18 Ar
4	19 K	🟩 20 Ca	🟩 21 Sc	🟥 22 Ti	🟥 23 V	🟨 24 Cr	25 Mn	🟩 26 Fe	27 Co	28 Ni	29 Cu	🟥 30 Zn	🟥 31 Ga	🟩 32 Ge	🟩 33 As	🟩 34 Se	🟩 35 Br	36 Kr
5	37 Rb	🟩 38 Sr	🟩 39 Y	🟥 40 Zr	🟥 41 Nb	🟥 42 Mo	🟥 43 Tc	🟥 44 Ru	🟥 45 Rh	🟨 46 Pd	47 Ag	🟥 48 Cd	🟥 49 In	🟥 50 Sn	🟩 51 Sb	🟩 52 Te	🟩 53 I	54 Xe
6	🟩 55 Cs	🟩 56 Ba	🟥 57 La	🟥 72 Hf	🟥 73 Ta	🟥 74 W	🟥 75 Re	🟥 76 Os	🟥 77 Ir	🟨 78 Pt	79 Au	🟥 80 Hg	🟥 81 Ti	🟥 82 Pb	🟩 83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 Ac	104 Rf	105 Ha	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Uub						

🟩 58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	🟩 63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	🟥 71 Lu
🟥 90 Th	🟥 91 Pa	🟥 92 U	93 Np	94 Pu	🟥 95 Am	96 Cm	97 Bk	98 Cr	99 Es	100 Fm	101 Md	102 No	103 Lr

All < 10 K, most (well) below 5 K
highest: Nb (Type II, 9.6 K)

Superconductivity: Nobel prizes

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 Nobel Prize in Physics 1972
"for their jointly developed theory of superconductivity, usually called the BCS-theory"
John Bardeen
Leon Neil Cooper
John Robert Schrieffer

The Nobel Prize in Physics 1973
"for [his] experimental discoveries regarding tunnelling phenomena in ... superconductors"
(Leo Esaki,) **Ivar Giaever**
"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"
Brian David Josephson

The Nobel Prize in Physics 1987
"for their important break-through in the discovery of superconductivity in ceramic materials"
J. Georg Bednorz
K. Alexander Müller

The Nobel Prize in Physics 2003
"for pioneering contributions to the theory of superconductors and superfluids"
Alexei A. Abrikosov
Vitaly L. Ginzburg
Anthony J. Leggett

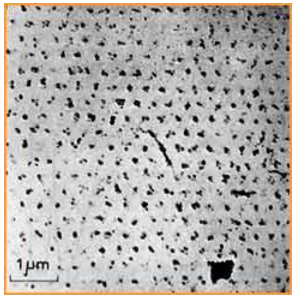
History

- 1895 liquid air (Carl von Linde)
- 1906 liquid helium (Heike Kamerlingh Onnes)
- 1911 discovery of superconductivity in Hg (4.2K)
  (H. Kamerlingh Onnes, Gilles Holst, Nobel prize 1913)
- 1933 discovery of “perfect diamagnetism” (Meissner, Ochsenfeld)
- 1935 London theory
- 1939 discovery of superfluidity of ^{4}He (Kapitza, Nobel prize 1978)
- 1950 Ginzberg-Landau theory (Nobel prize 2003)
- 1950 theory for attractive e-e interaction mediated by phonons (Froehlich, Bardeen)
- 1957 BCS theory (Bardeen, Cooper, Schrieffer, Nobel prize 1996)
- 1962 Prediction of Josephson effects (Nobel prize 1973)
- 1964 discovery of superfluidity of ^{3}He (Lee, Osheroff, Richardson, Nobel prize 1996)
- 1975 theory of superfluidity of ^{3}He (Leggett, nobel prize 2003)

Since then many breakthroughs (some in cologne):

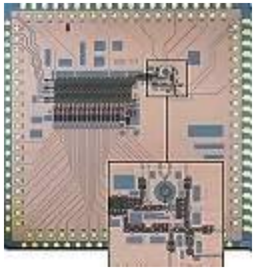
Reentrant SC (1970, Mueller-Hartmann, Zittartz), Heavy fermion SC (1979, steglich), Organic superconductors, High T_c’s (1986, Bednorz, Mueller, Nobel prize 1987), d-wave (cuprates) and p-wave (Sr_2RuO_4), intermetallics (MgB_2), Fe-pnictides, coupling to magnetic order, topological superconductivity, …

Why superconductivity

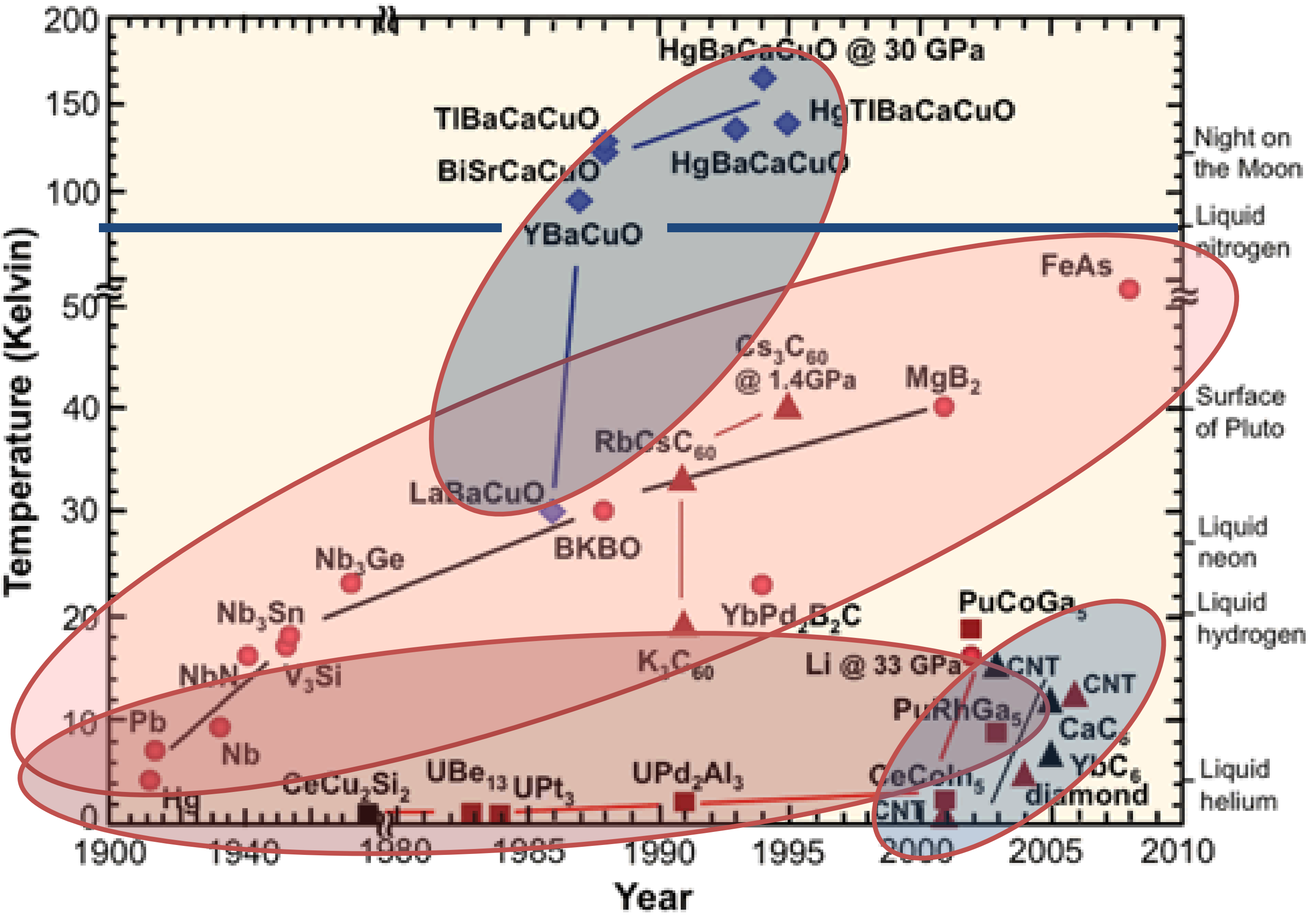


Essmann and Trauble, 1967

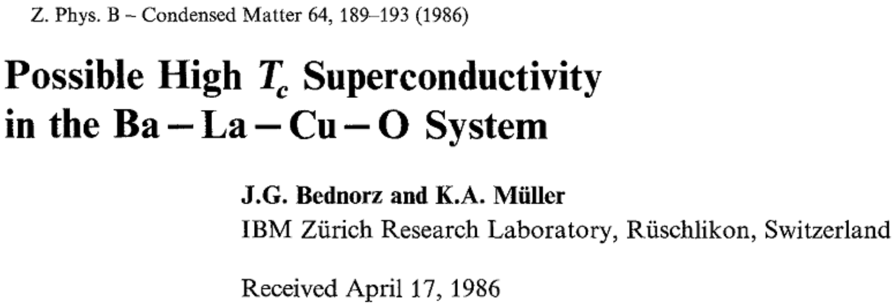
- Fascinating physics
  - Zero resistance
  - Macroscopic quantum behavior,
  - Many body physics, well beyond single particle picture (currently)
  - Levitation and high speed trains
- BCS works well for some compounds, but many are not understood (cuprates!)
  - Work for theorists and experimentalists
- Sparks new theory and experiment
- Keeps surprising (*rara avis in terris nigroque simillima cygno, Juvennal, 1st BC)*
  - High T_c's
  - Role of magnetism
  - Superconducting compounds with Fe (pnictides)
- Applications
  - Fast trains
  - High frequency electronics
  - Lossless powertransport
  - High field coils, bending magnets at CERN
  - Medical MRI
  - Sensitive magnetic field sensors
  - Etc. etc.



Superconductors: Timeline



High temperature superconductivity



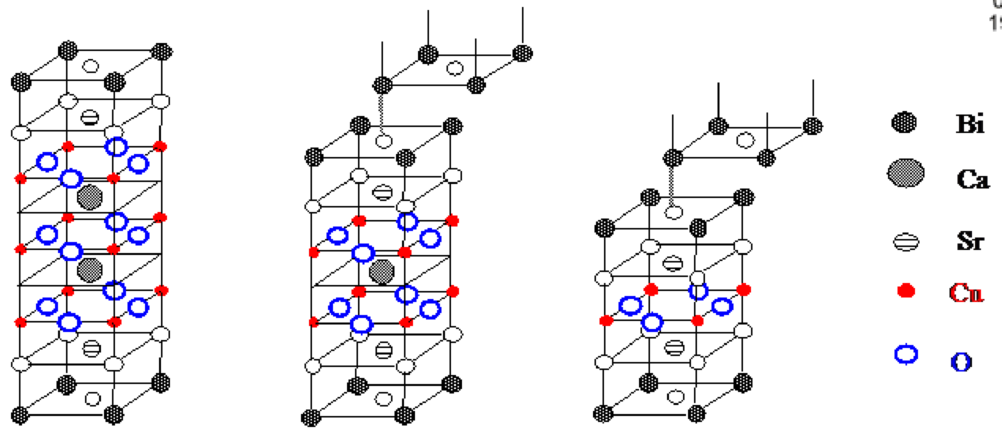
Z. Phys. B – Condensed Matter 64, 189–193 (1986)

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

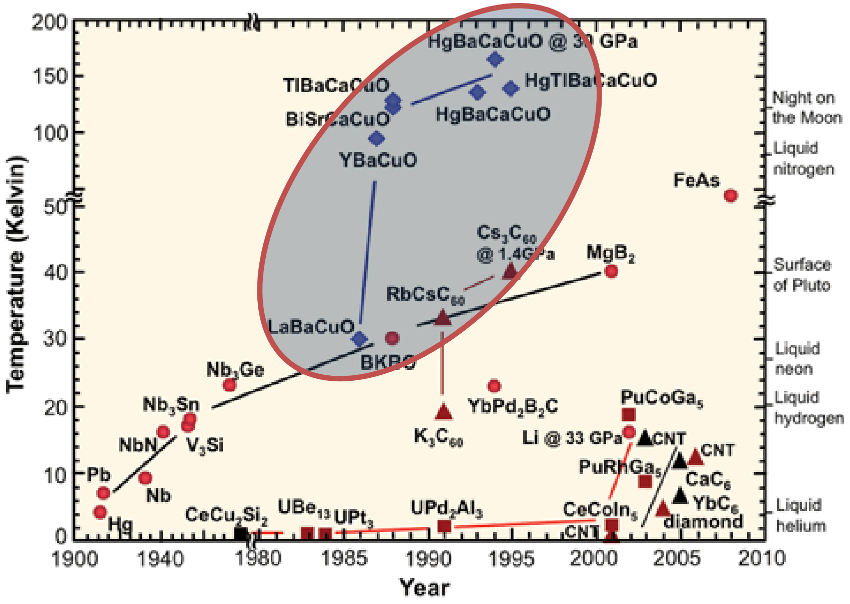
CuO planes are the key components of high T_c superconductors



$Bi_2Sr_2Ca_2Cu_3O_{10}$ Bi2223 — (3 CuO L) T_c = 105 K

$Bi_2Sr_2CaCu_2O_8$ Bi2212 — (2 CuO L) T_c = 92 K

$Bi_2Sr_2CuO_6$ Bi2201 — (1 CuO L) T_c = 0 ~ 20 K



High Tc superconductors

Critical temperature (Tc), crystal structure and lattice constants of some high-Tc superconductors

Formula	Notation	T_c (K)	No. of Cu-O planes in unit cell	Crystal structure
$YBa_2Cu_3O_7$	123	92	2	Orthorhombic
$Bi_2Sr_2CuO_6$	Bi-2201	20	1	Tetragonal
$Bi_2Sr_2CaCu_2O_8$	Bi-2212	85	2	Tetragonal
$Bi_2Sr_2Ca_2Cu_3O_6$	Bi-2223	110	3	Tetragonal
$Tl_2Ba_2CuO_6$	Tl-2201	80	1	Tetragonal
$Tl_2Ba_2CaCu_2O_8$	Tl-2212	108	2	Tetragonal
$Tl_2Ba_2Ca_2Cu_3O_{10}$	Tl-2223	125	3	Tetragonal
$TlBa_2Ca_3Cu_4O_{11}$	Tl-1234	122	4	Tetragonal
$HgBa_2CuO_4$	Hg-1201	94	1	Tetragonal
$HgBa_2CaCu_2O_6$	Hg-1212	128	2	Tetragonal
$HgBa_2Ca_2Cu_3O_8$	Hg-1223	134	3	Tetragonal

Hg-1223: 153 K under pressure

New record (???)

Conventional superconductivity at 190 K at high pressures

A.P. Drozdov, M. I. Eremets, I. A. Troyan

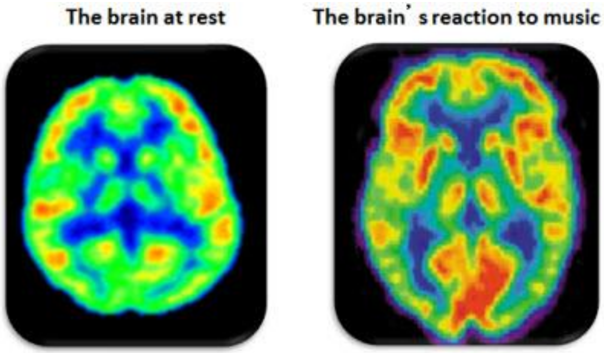
(Submitted on 1 Dec 2014)

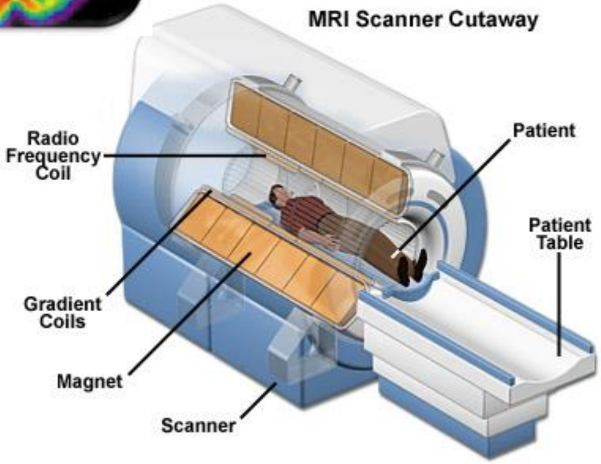
The highest critical temperature of superconductivity Tc has been achieved in cuprates: 133 K at ambient pressure and 164 K at high pressures. As the nature of superconductivity in these materials is still not disclosed, the prospects for a higher Tc are not clear. In contrast the Bardeen-Cooper-Schrieffer (BCS) theory gives a clear guide for achieving high Tc: it should be a favorable combination of high frequency phonons, strong coupling between electrons and phonons, and high density of states. These conditions can be fulfilled for metallic hydrogen and covalent hydrogen dominant compounds. Numerous followed calculations supported this idea and predicted Tc=100-235 K for many hydrides but only moderate Tc~17 K has been observed experimentally. Here we found that sulfur hydride transforms at P~90 GPa to metal and superconductor with Tc increasing with pressure to 150 K at ~200 GPa. This is in general agreement with recent calculations of Tc~80 K for H2S. Moreover we found **superconductivity with Tc~190 K** in a H2S sample pressurized to P>150 GPa at T>220 K. This superconductivity likely associates with the dissociation of H2S, and formation of SHn (n>2) hydrides. We proved occurrence of superconductivity by the drop of the resistivity at least 50 times lower than the copper resistivity, the decrease of Tc with magnetic field, and the strong isotope shift of Tc in D2S which evidences a major role of phonons in the superconductivity. H2S is a substance with a moderate content of hydrogen therefore high Tc can be expected in a wide range of hydrogen-contain materials. Hydrogen atoms seem to be essential to provide the high frequency modes in the phonon spectrum and the strong electron-phonon coupling.

arXiv:1412.0460 (http://arxiv.org/abs/1412.0460)

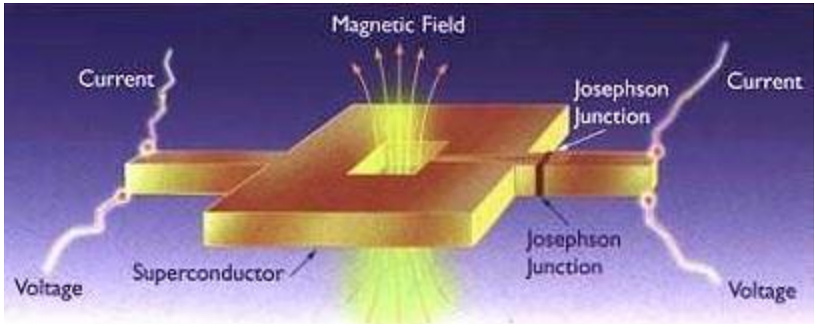
Applications

MRI imaging



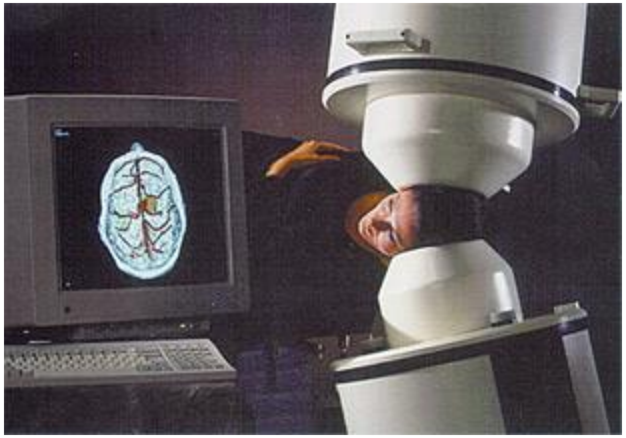


SQUID



http://www.wou.edu/~rmiller09/superconductivity/squid.jpg

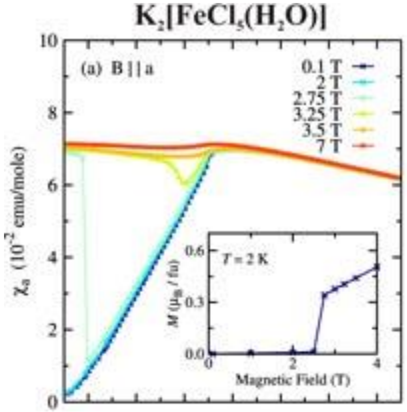
Mapping biomagnetism

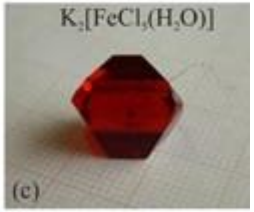


https://www.medphysics.wisc.edu/research/biomag/images/Squid1.jpg

Applications

SQUID magnetometry





Ackerman et al.
J.Phys.Cond.Mat. 2014

Sensitivity ~ 1 fT (fraction of a quantum flux)
(10^{-11} times earth magnetic field)
Human brain: few fT
Human hart: 50.000 fT

Ultraprecision gyroscopes
(3 10^{-8} degree)

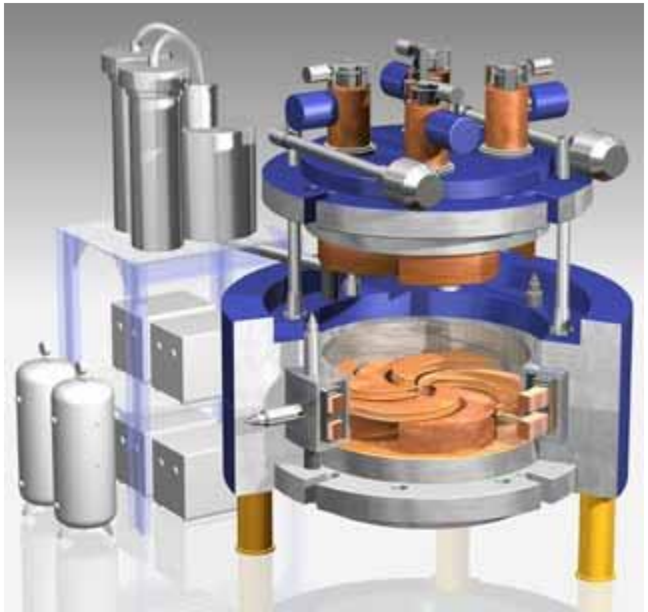
Gravity probe B proved once again that Einstein was correct (2004-2010)

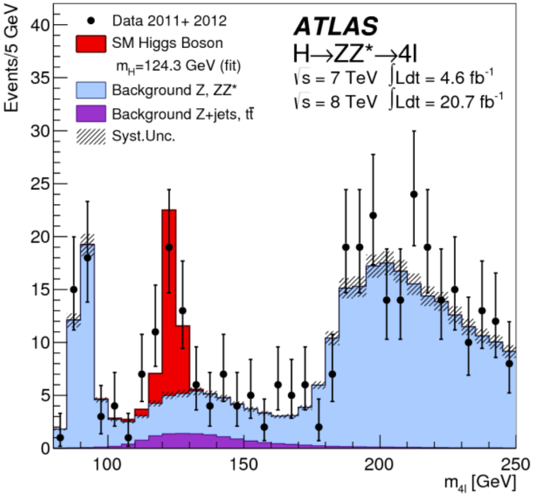
The experiment, launched in 2004, used four ultra-precise gyroscopes to measure the hypothesized geodetic effect, the warping of space and time around a gravitational body, and frame-dragging, the amount a spinning object pulls space and time with it as it rotates. GP-B determined both effects with unprecedented precision by pointing at a single star, IM Pegasi, while in a polar orbit around Earth.

Applications

Large Hadron Collider (CERN)

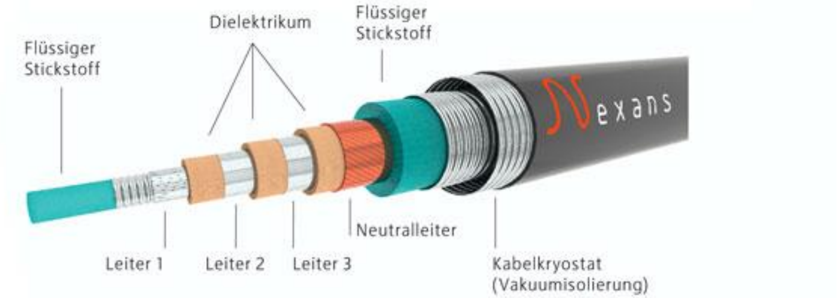
Proton therapy



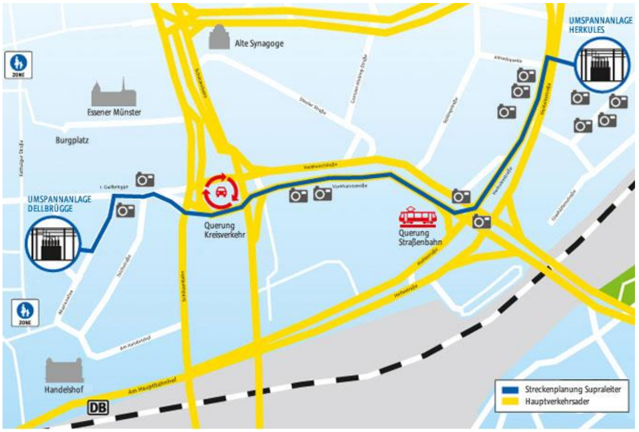


Applications

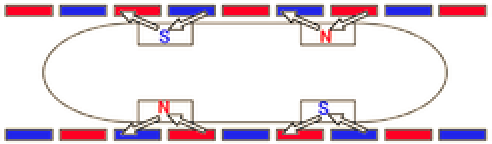
Power lines (conventional, 1% loss/150km)



RWE, Essen (1 km)

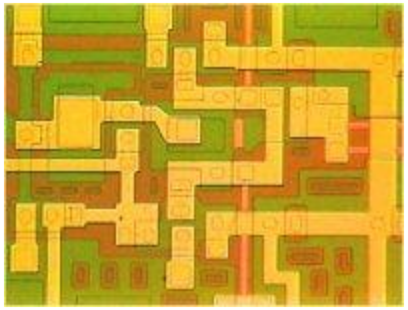


MAGLEV train, Japan
(operational 2027, Tokyo-Nagoya)



And many more applications…

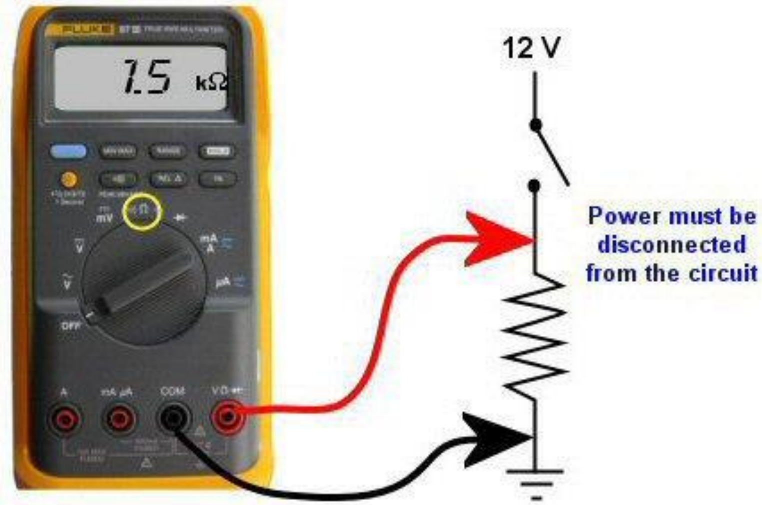
Superconductors: Main properties



- Macroscopic quantum phenomenon

- Vanishing resistance → Kamerlingh Onnes
- Perfect diamagnet → Meissner-Ochsenfeld effect
  - Type I and type II superconductors
- 2nd order phase transition → Thermodynamics (Heat cap.)
- Electronically gapped state → Tunneling spectroscopy, optics
- Isotope effect: Role of phonons? → Isotope experiments
- Unit of charge 'responsible particle' is 2e → Flux quantization

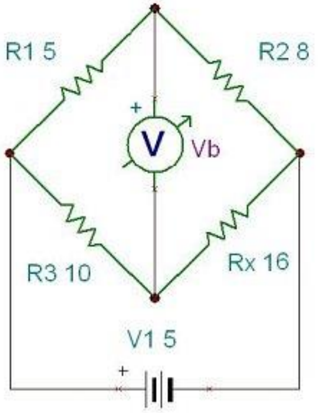
Zero resistance



Power must be disconnected from the circuit

Fig. 12-13 - Measuring Resistance

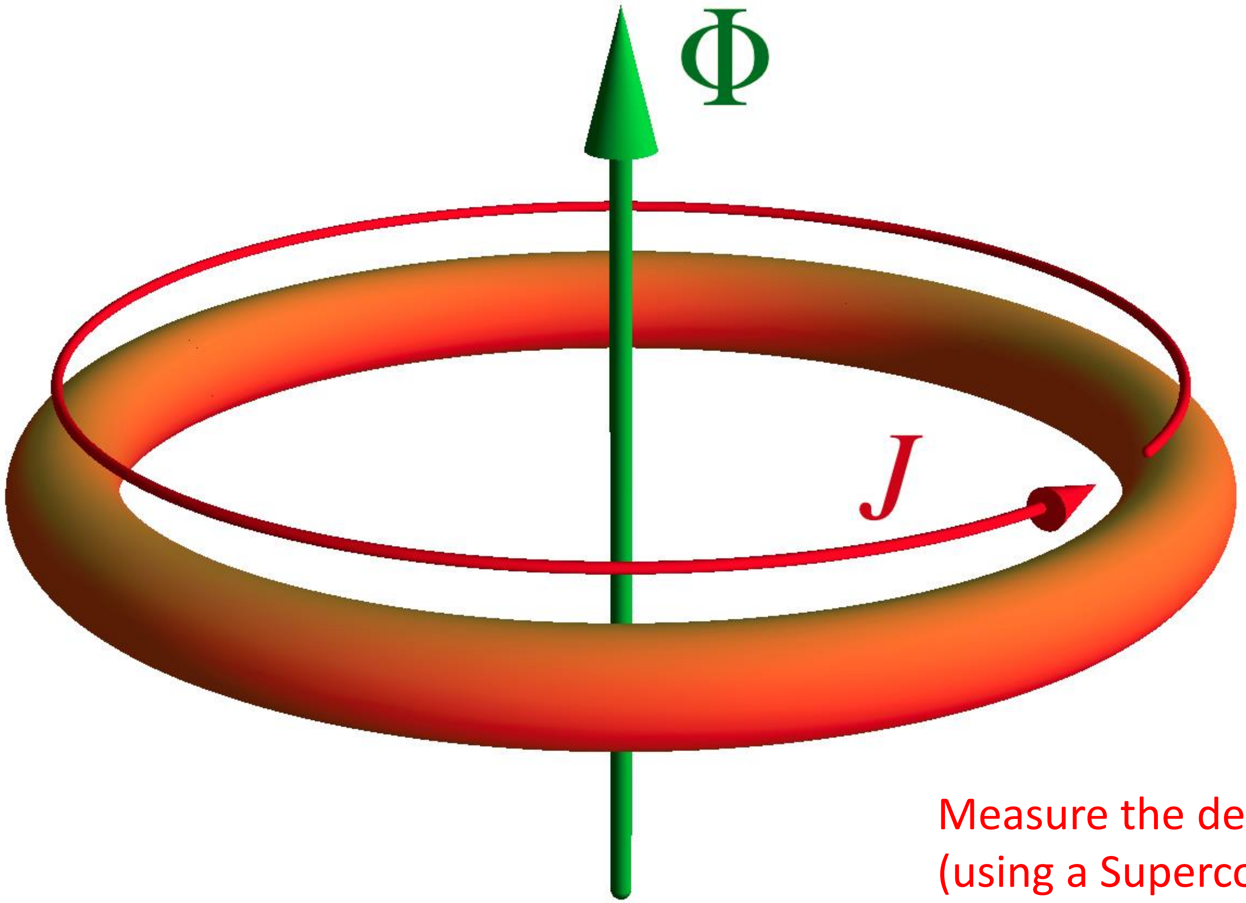
Wheatstone bridge



Condition of ballance:

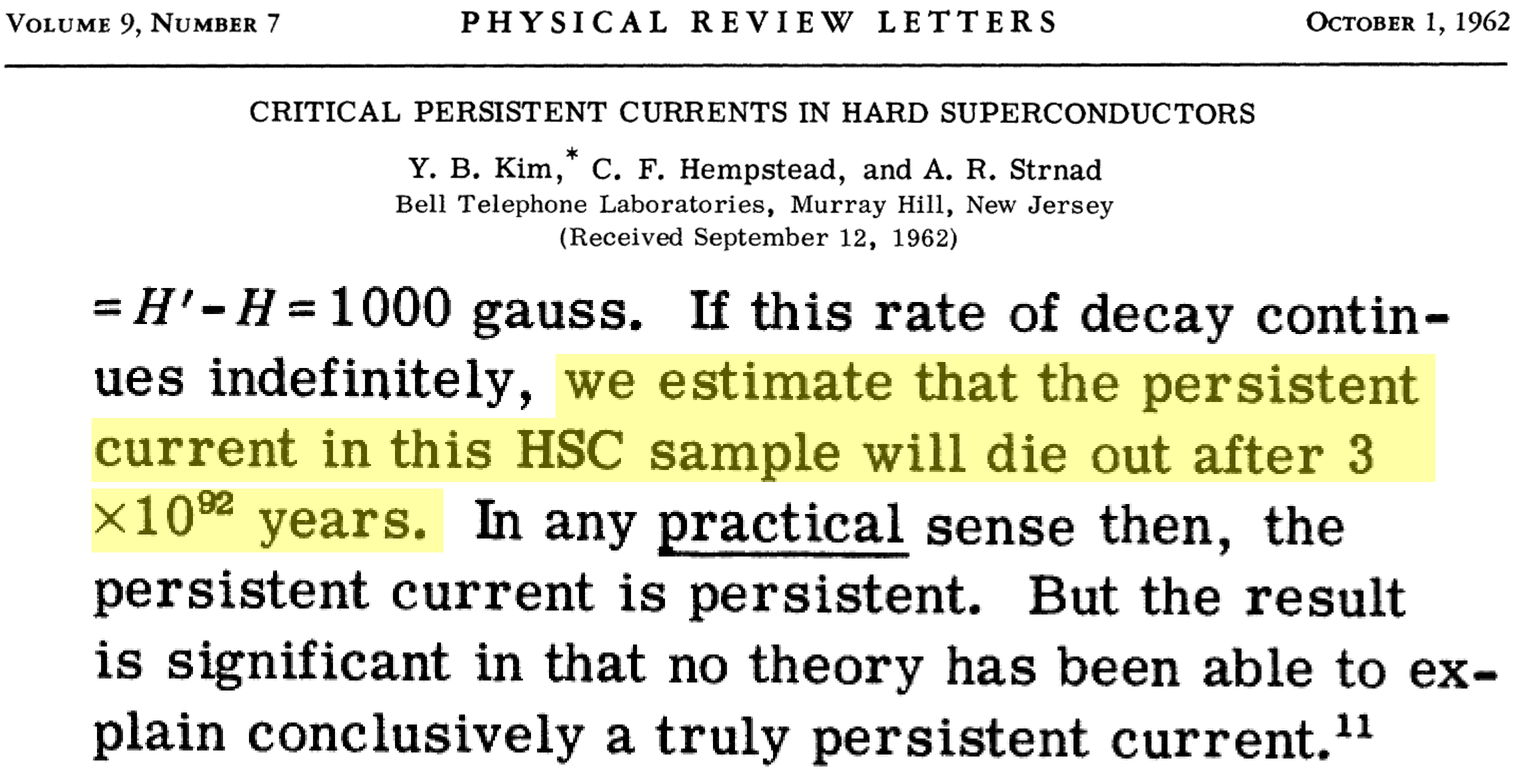
$$R_x = \frac{R_2 R_3}{R_1}$$

Zero resistance



Measure the decay of the flux
(using a Superconducting Quantum
Interference Device)

Zero resistance



VOLUME 9, NUMBER 7 PHYSICAL REVIEW LETTERS OCTOBER 1, 1962

CRITICAL PERSISTENT CURRENTS IN HARD SUPERCONDUCTORS

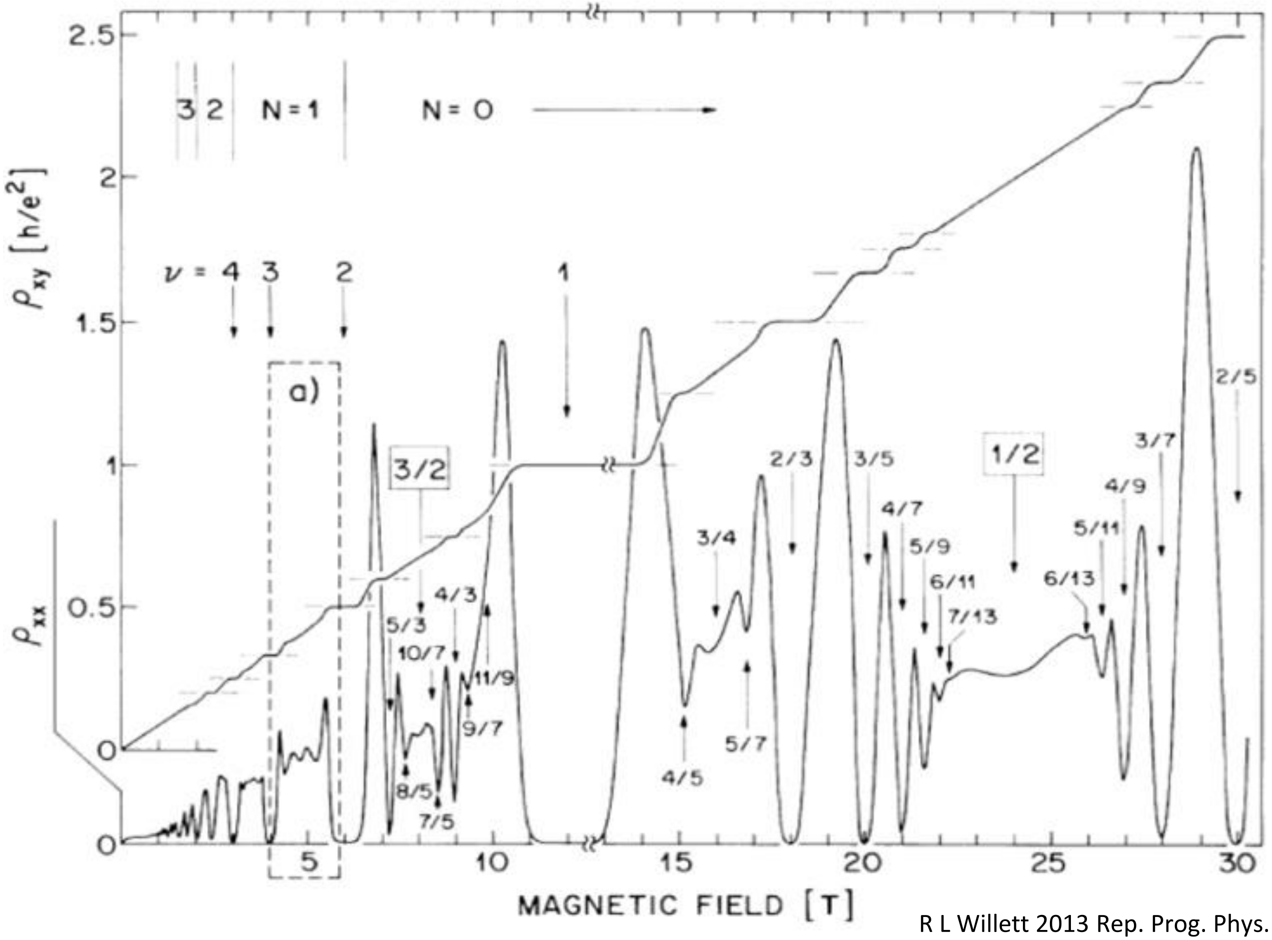
Y. B. Kim,* C. F. Hempstead, and A. R. Strnad
Bell Telephone Laboratories, Murray Hill, New Jersey

(Received September 12, 1962)

$= H' - H = 1000$ gauss. If this rate of decay continues indefinitely, we estimate that the persistent current in this HSC sample will die out after 3×10^{92} years. In any practical sense then, the persistent current is persistent. But the result is significant in that no theory has been able to explain conclusively a truly persistent current.[11]

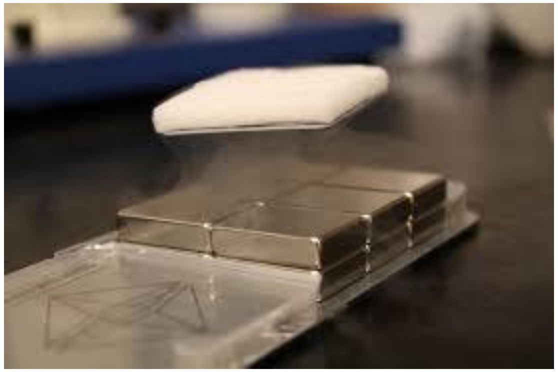
Expts. on 3Nb-Zr alloys

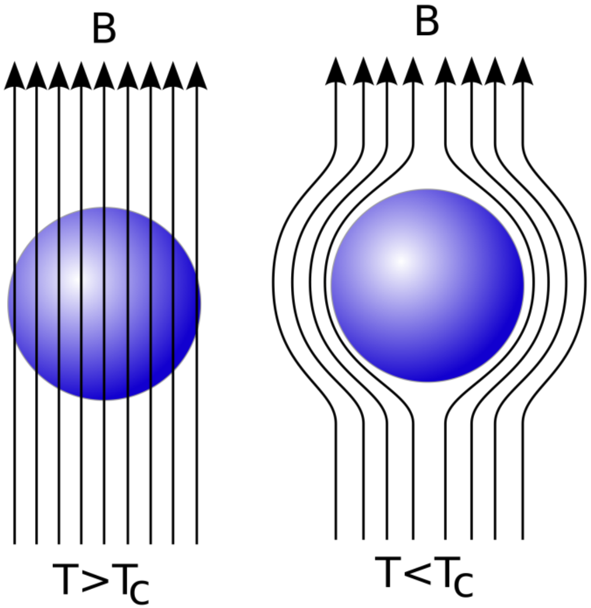
Zero resistance



R L Willett 2013 Rep. Prog. Phys.

Meissner-Ochsenfeld effect





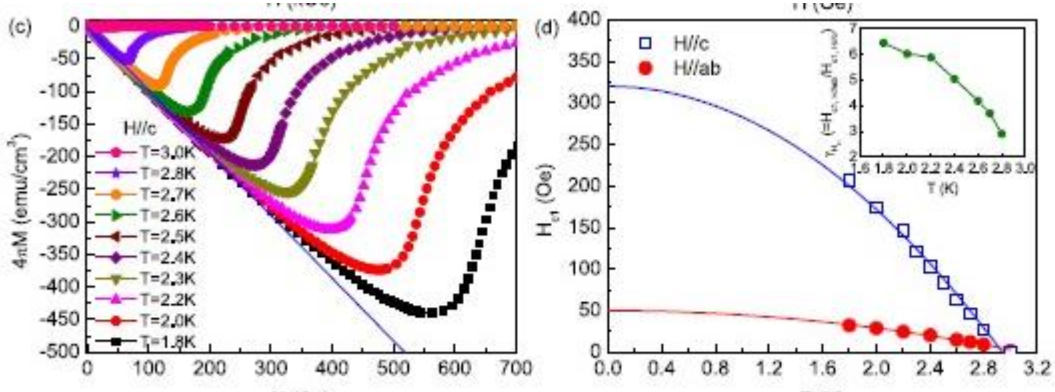


Figure Ni$_{0.05}$ZrTe$_3$: (c) Low-field parts of $M(H)$ at various temperature for $H||c$ with demagnetization correct, respectively. (d) Temperature dependence of H_{c1} for $H||ab$ and $H||c$. The dashed lines are the fitted lines using $H_{c1} = H_{c1}(0)(1 - (T/T_c)^2)$. [Lei et al. 2011]