Condensed Matter Physics II
SS 2015

Wednesday 9:30-12:30

Seminar Room Physics 2

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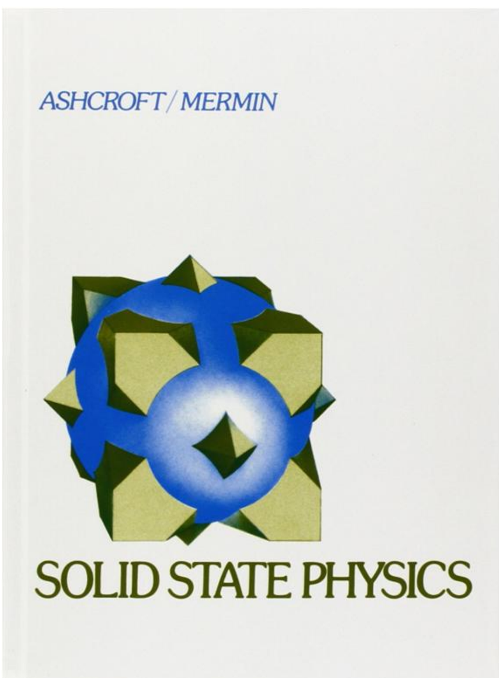
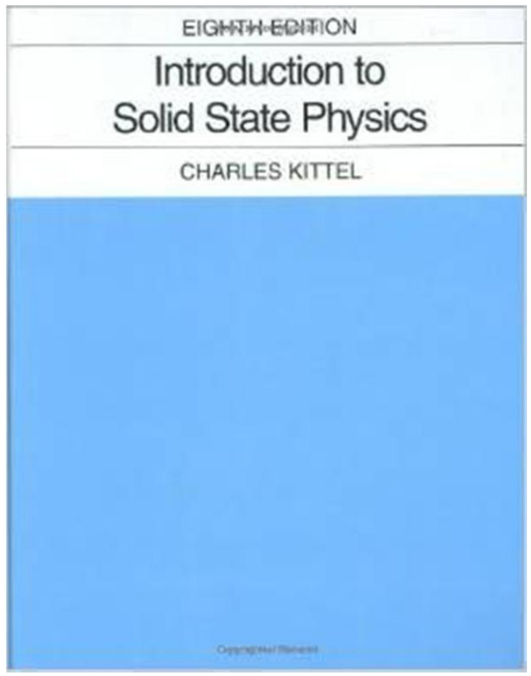
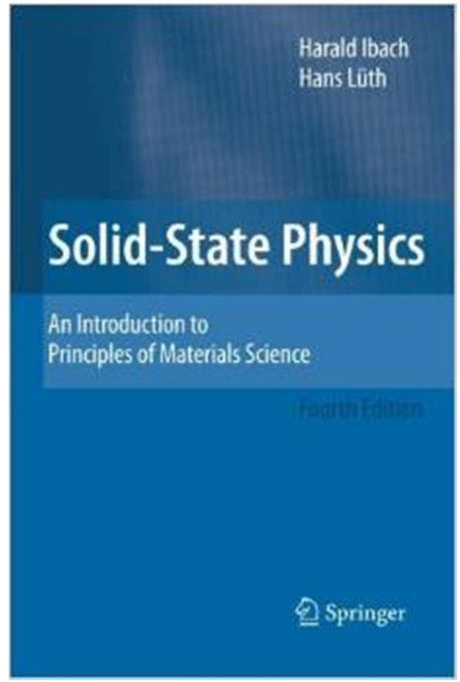
Literature

- Basic solid state physics book:
  - Ashcroft and Mermin
  - Kittel
  - Ibach Luth







Images and Tables

Many of the images used in the lectures originate from the web, in particular sites like

Wikipedia
Hyperphysics
Superconductors.org

turn out to be useful (but are not the only ones)

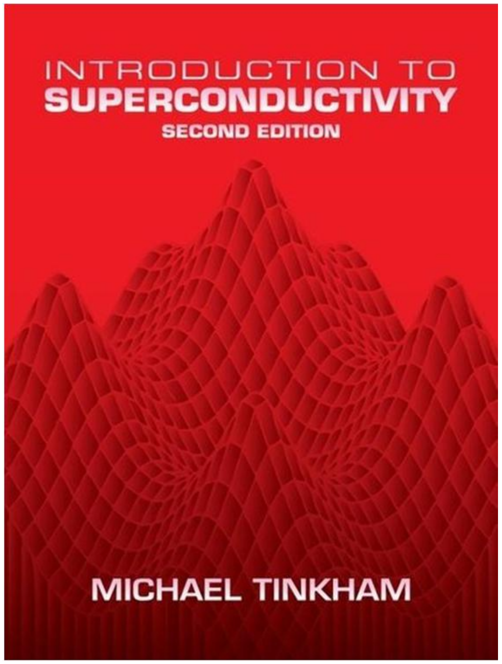
Preliminary Schedule

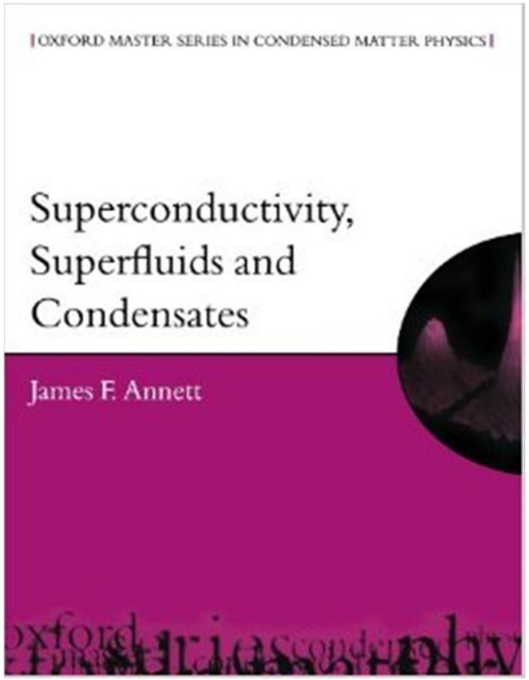
1	8-Apr-15	PvL	Superconductivity
2	15-Apr-15	PvL	Superconductivity
3	22-Apr-15	PvL	Superconductivity
4	29-Apr-15	PvL	Ordering phenomena
5	6-May-15	PvL	Ordering phenomena
6	13-May-15	PvL	Ordering phenomena
7	20-May-15	IV	Dielectrics and ferroelectrics, multiferroics
8	27-May-15	IV	Thin film physics
9	3-Jun-15	IV	Thin film fabrication techniques
10	10-Jun-15	PvL	Transport
11	17-Jun-15	PvL	Transport
12	24-Jun-15	PvL	NMR/ESR
13	1-Jul-15	PvL	Magneto-optical properties
14	8-Jul-15	PvL	Bose Einstein condensation
15	15-Jul-15	PvL	Thermo-electrics

Literature superconductivity

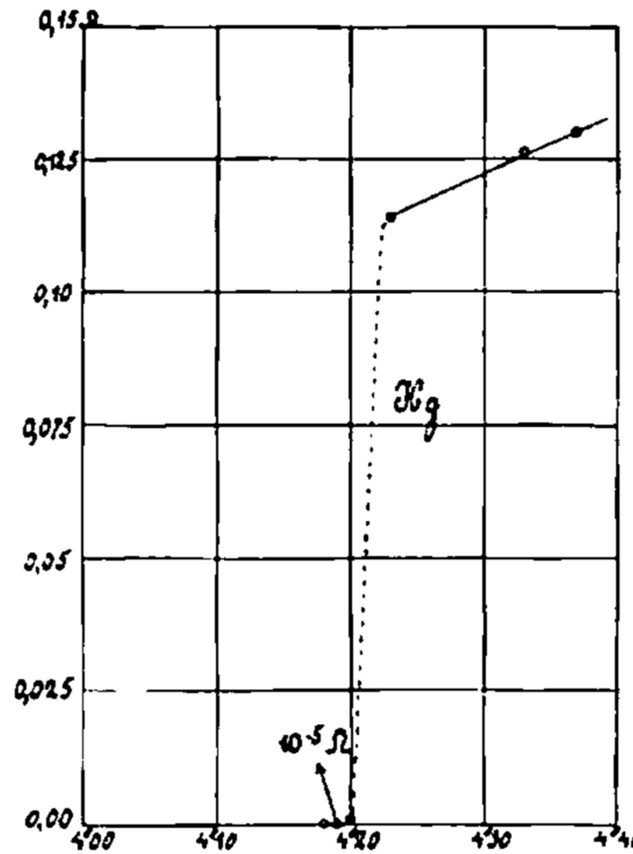
Solid state physics books

PLUS





Superconductivity



1908 Liquid Helium
1911 Superconductivity

1913 Nobel Prize

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

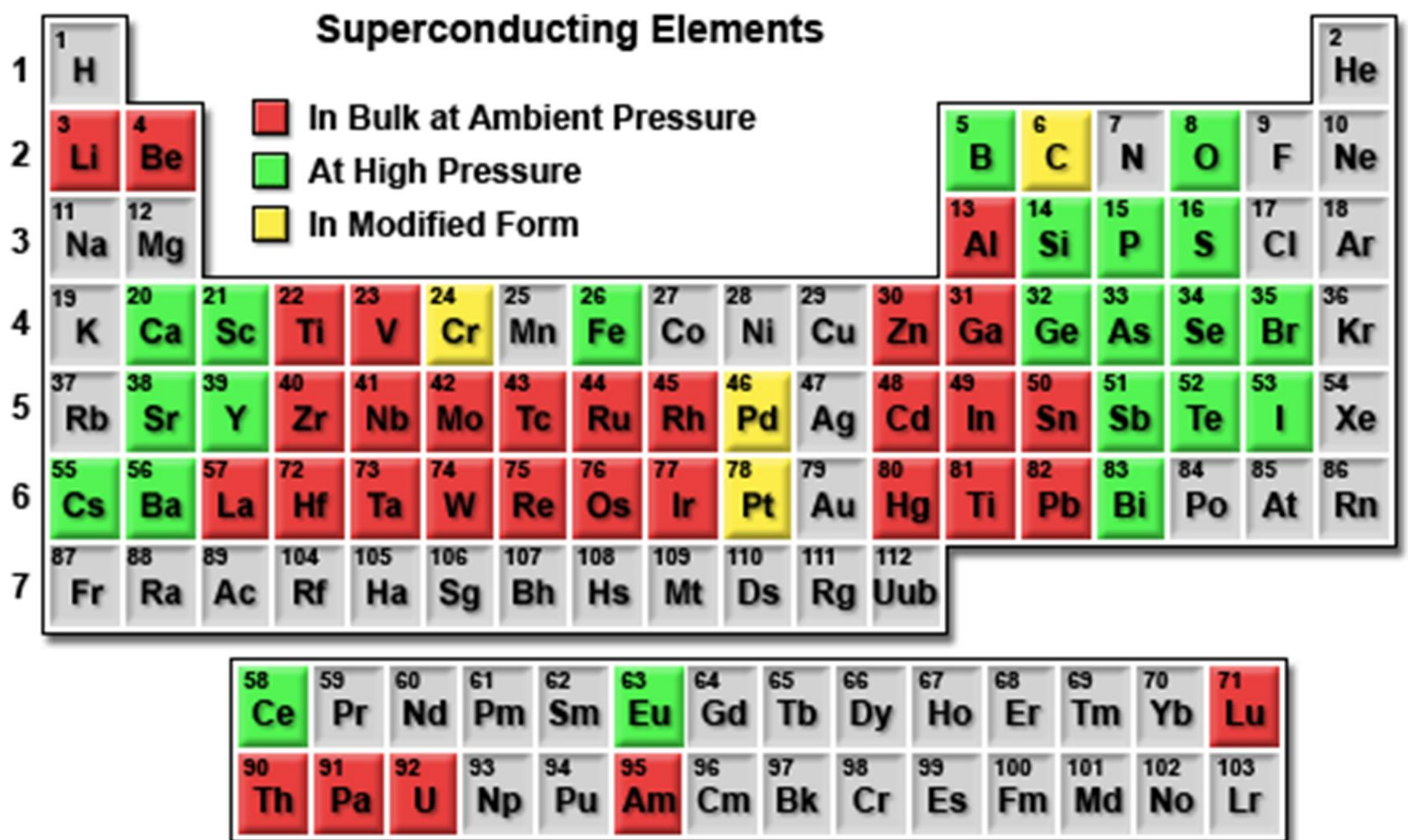
The Nobel Prize in Physics 1972
"for their jointly developed theory of superconductivity, usually called the BCS-theory"
John Bardeen
Leon Neil Cooper
John Robert Schrieffer

The Nobel Prize in Physics 1973
"for [his] experimental discoveries regarding tunneling 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

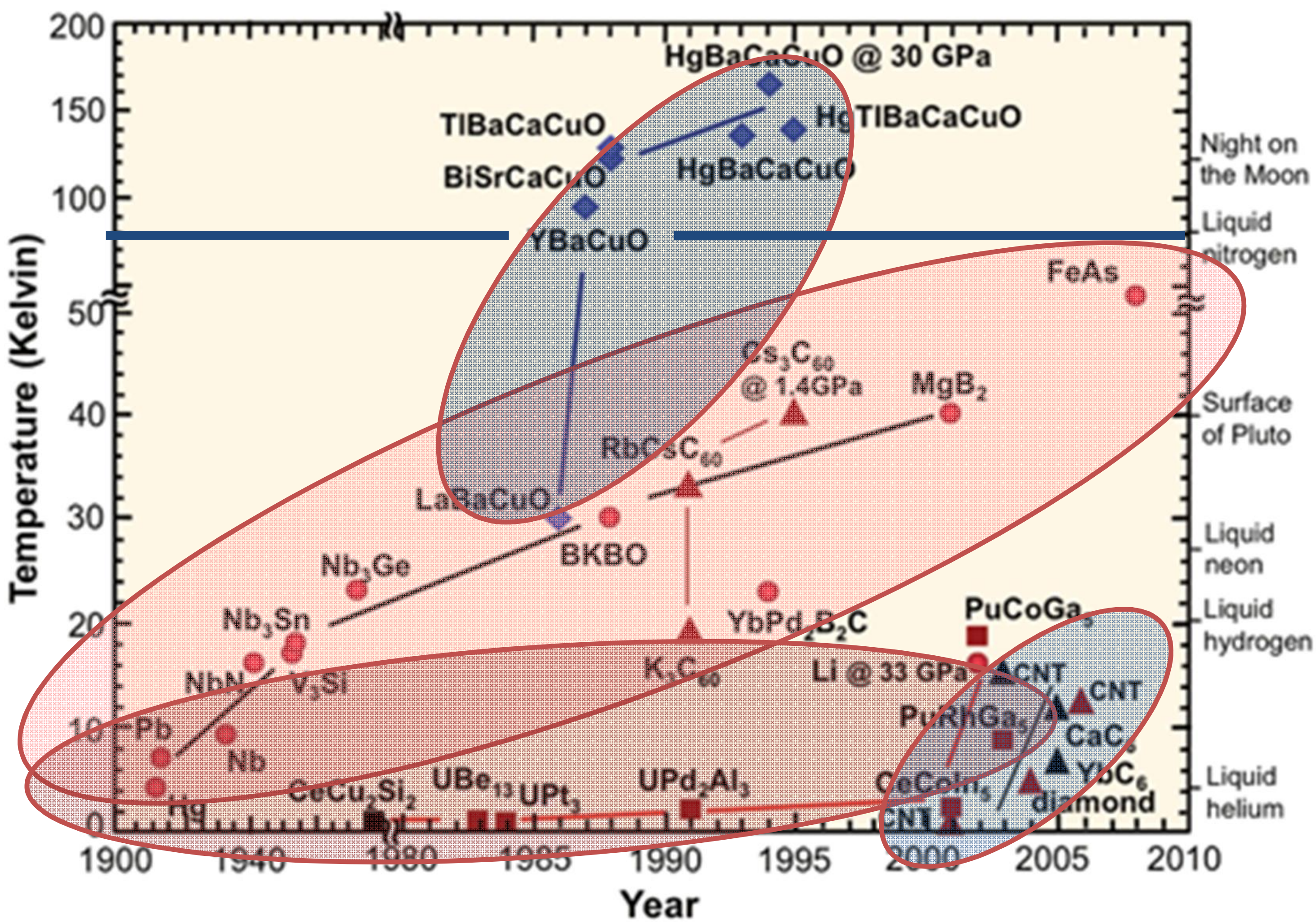
The Nobel Prize in Physics 2003
"for pioneering contributions to the theory of superconductors and superfluids"
Alexei A. Abrikosov
Vitaly L. Ginzburg
Anthony J. Leggett

Superconducting elements



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

Superconductors: Timeline



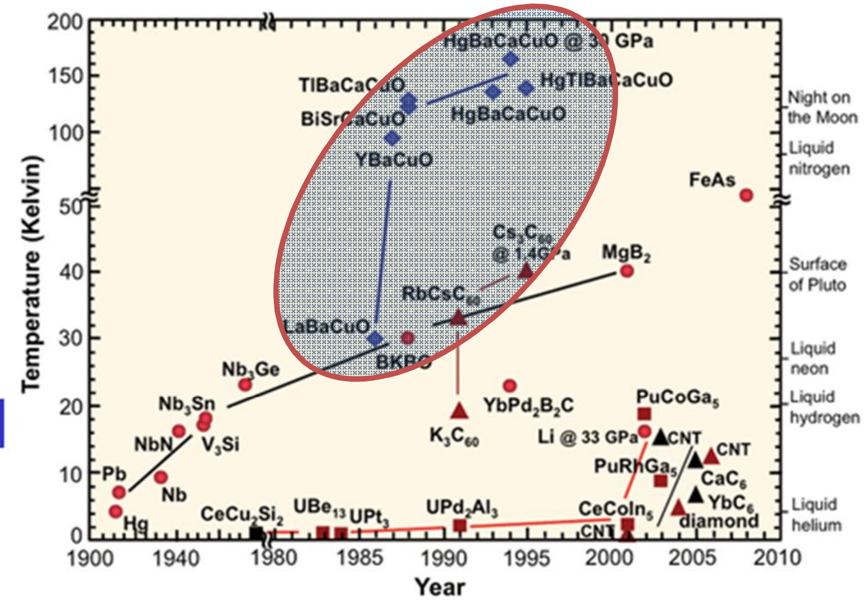
High temperature superconductivity

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

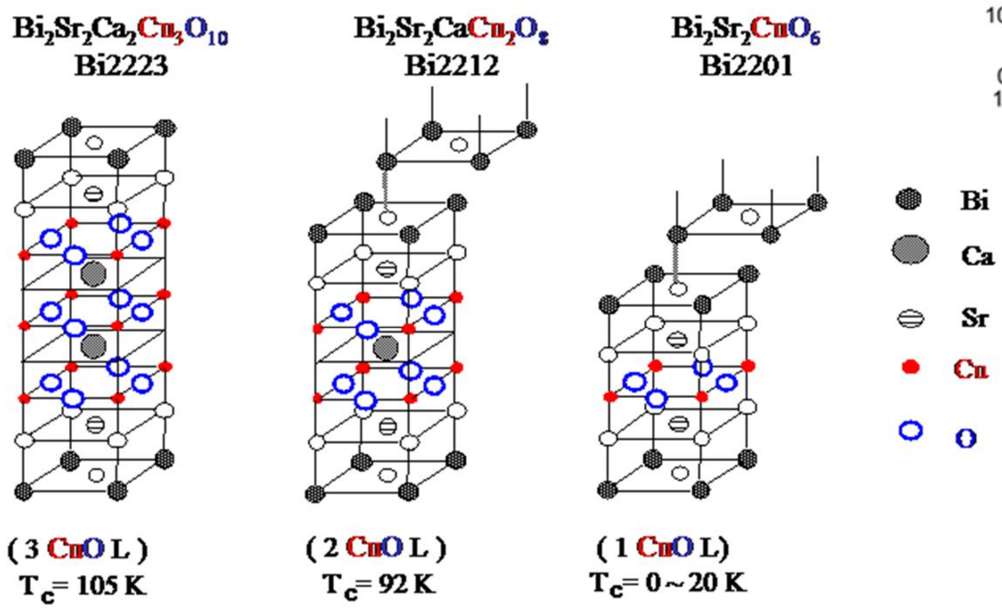
Possible High T_c Superconductivity in the Ba – La – Cu – O System

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



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

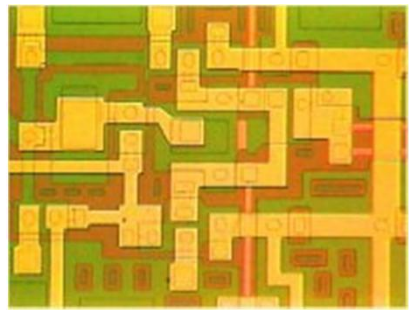
A.P. Drozdov, M. I. Eremets, I. A. Troyan

(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)

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

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

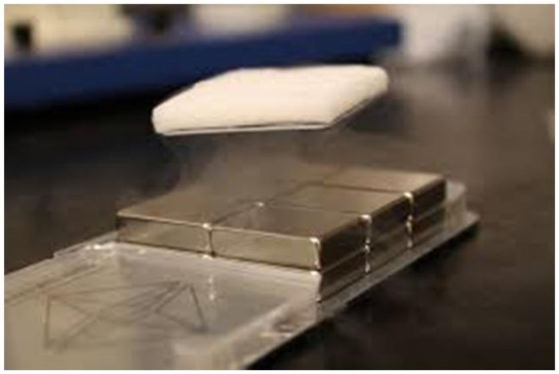
CRITICAL PERSISTENT CURRENTS IN HARD SUPERCONDUCTORS

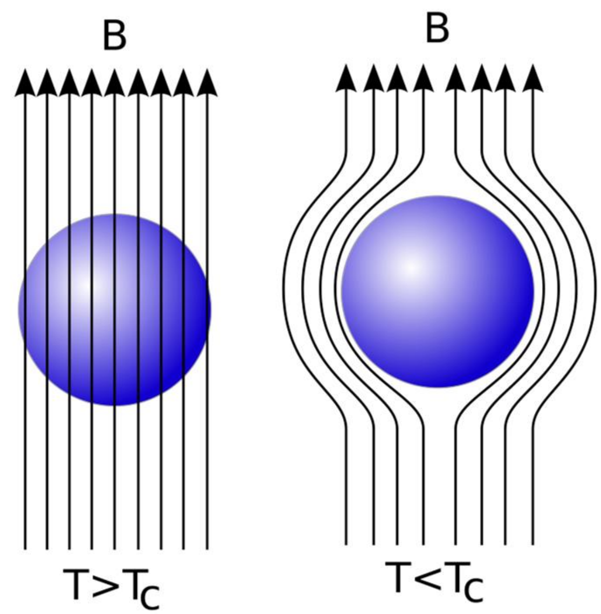
Y. B. Kim,* C. F. Hempstead, and A. R. Strnad
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received September 12, 1962)

$= H' - H = 1000$ 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

Meissner-Ochsenfeld effect





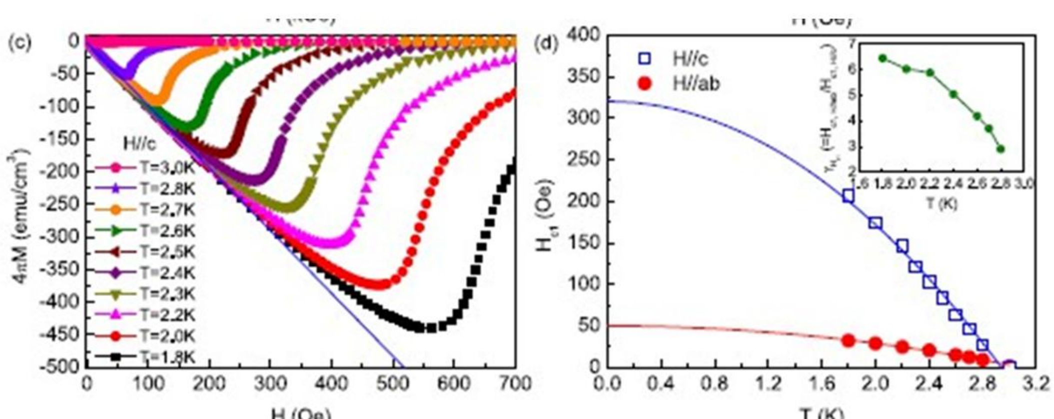
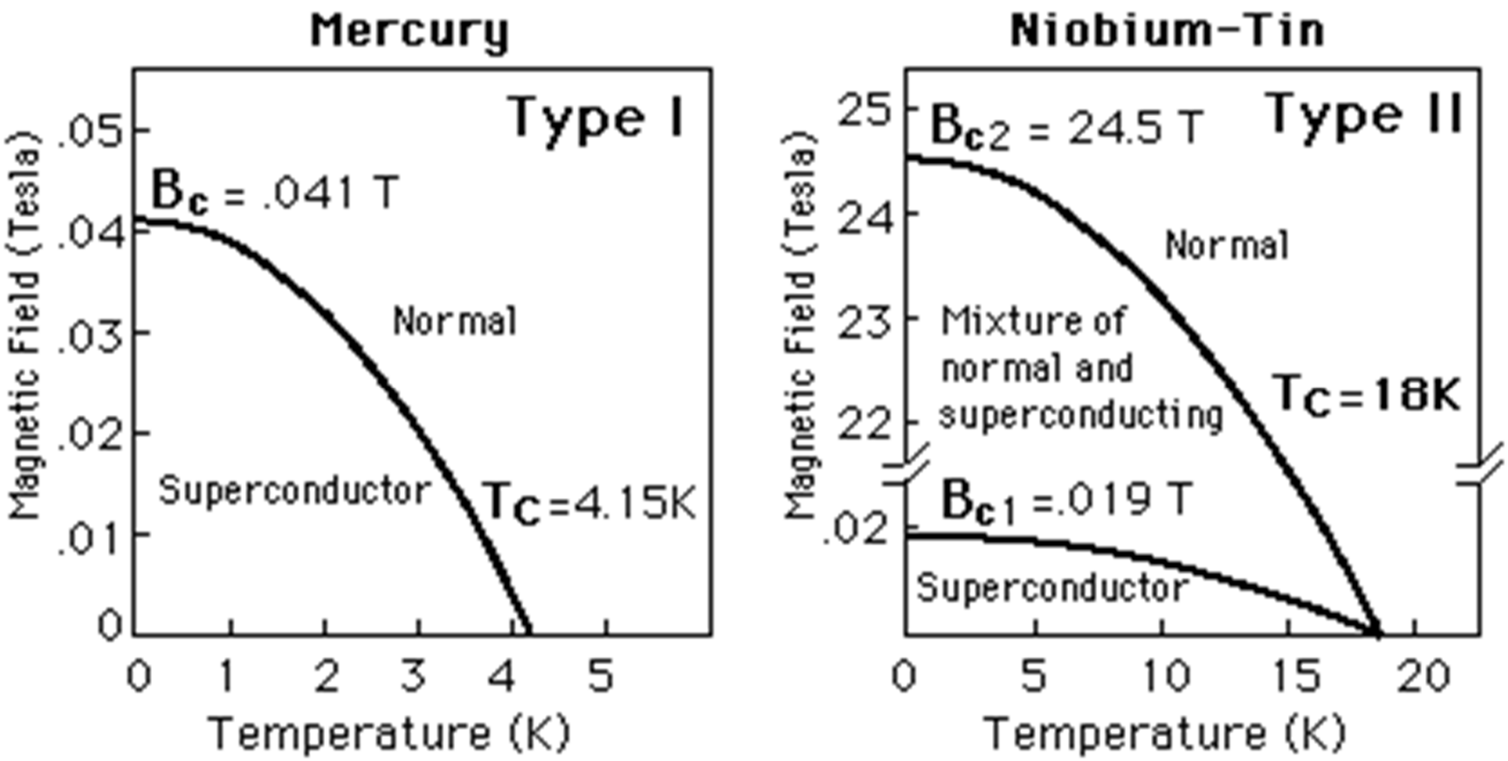
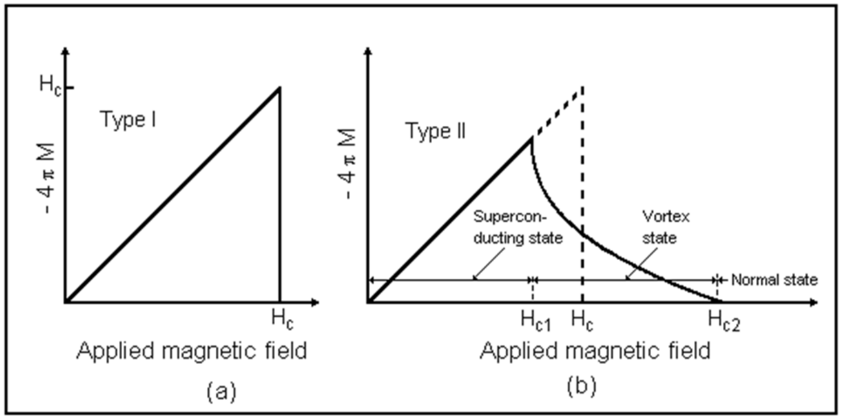


Figure $Ni_{0.05}ZrTe_3$: (c) Low-field parts of $M(H)$ at various temperature for $H||c$ with demagnetization correct, respectively. (d) Temperature dependence of H_{c1} for $H||ab$ and $H||c$. The dashed lines are the fitted lines using $H_{c1} = H_{c1}(0)(1 - (T/T_c)^2)$. [Lei et al. 2011]

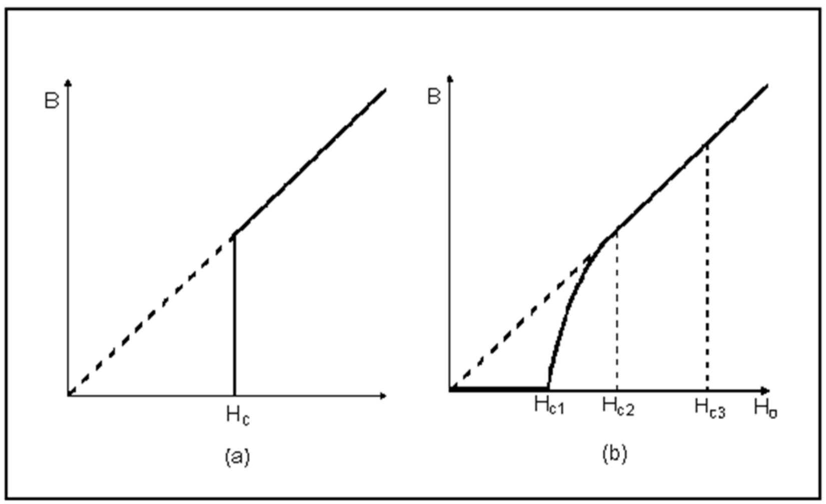
Type I & II superconductors



Type I & II superconductors

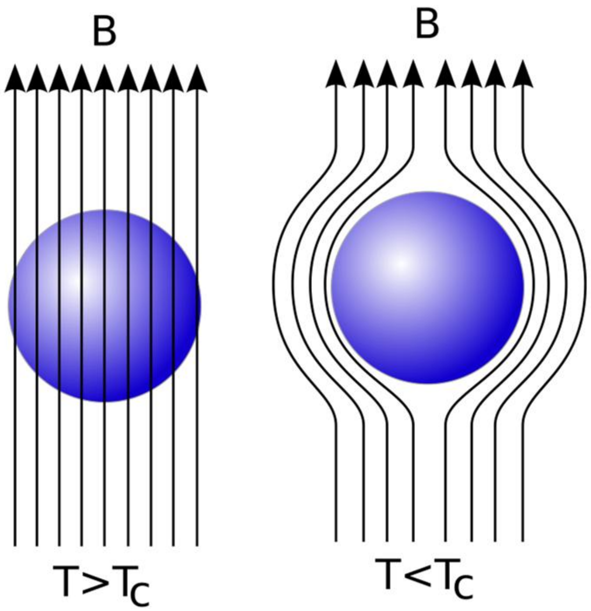


Magnetization M

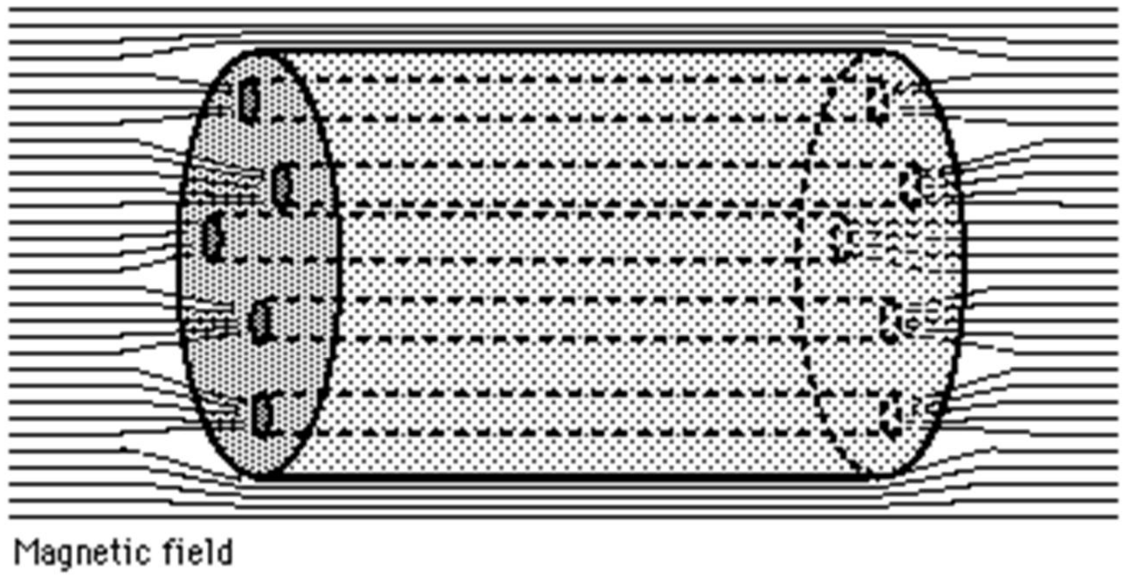


Magnetic induction B

Type II superconductors



TYPE I



TYPE II
(shubnikov phase)

Flux lines, Abrikosov lattice

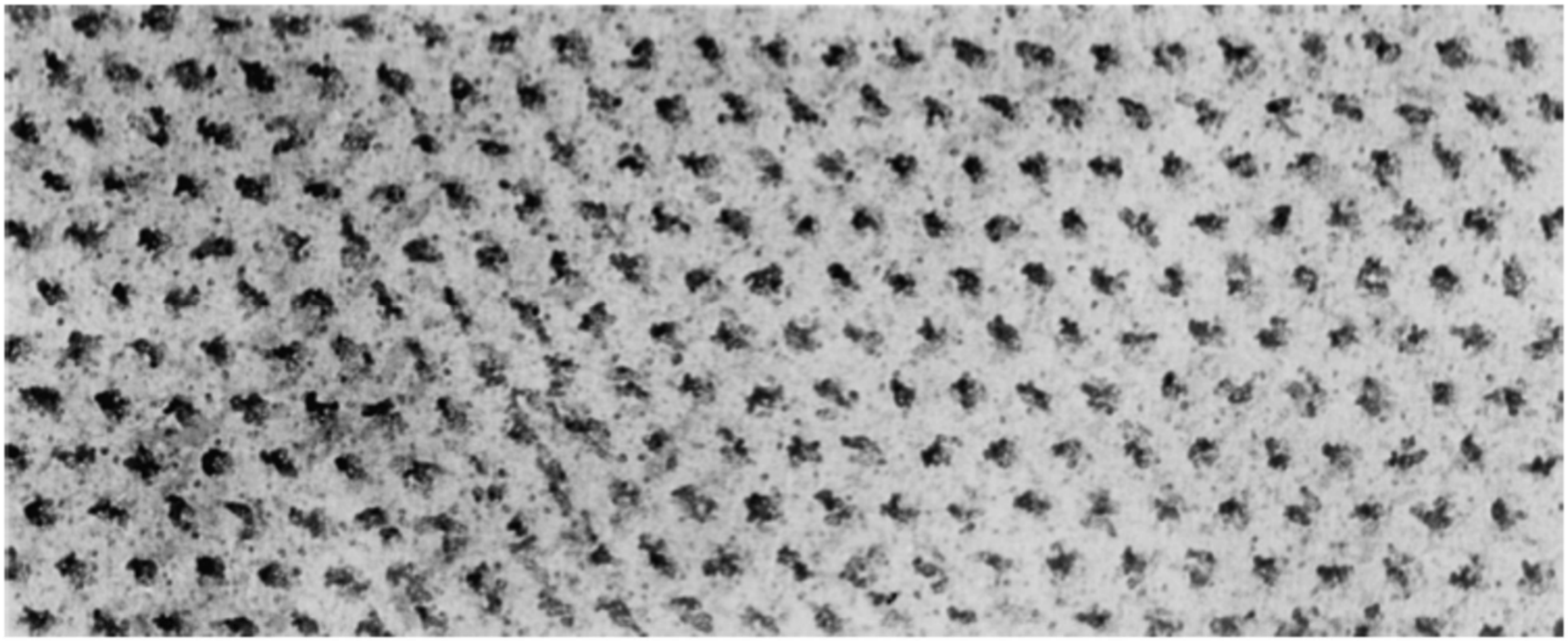


Fig. 1.9 Image of the vortex lattice obtained with an electron microscope following the decoration with iron colloid. Frozen-in flux after the magnetic field has been reduced to zero. Material: Pb + 6.3 at.% In; temperature: 1.2 K; sample shape: cylinder, 60 mm long, 4 mm diameter; magnetic field $\mathbf{B}_a$ parallel to the axis. Magnification: 8300×. (Reproduced by courtesy of Dr. Essmann).

Lattice: 1-100 nm

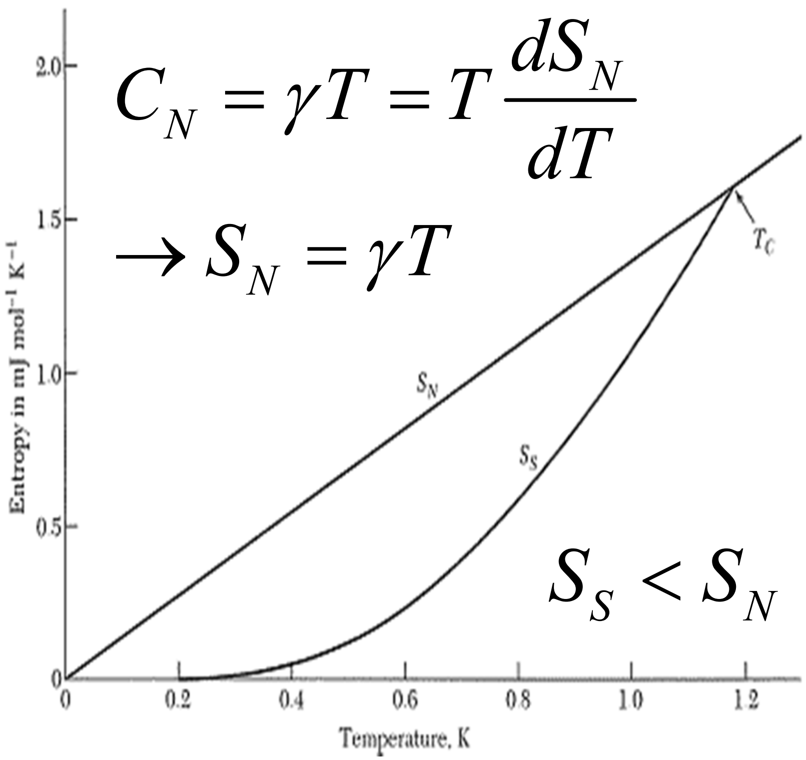
Second order phase transition

Aluminum

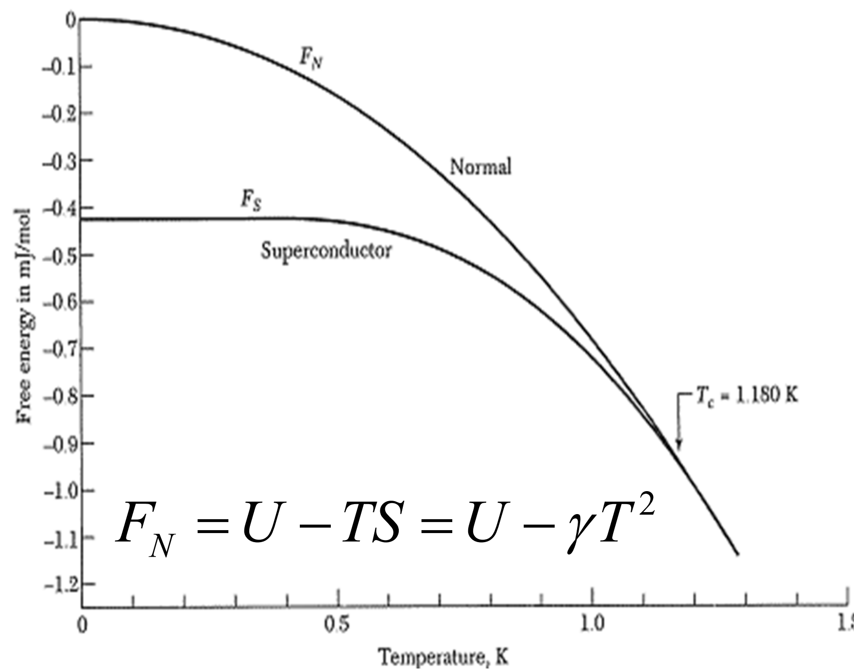
$$C_N = \gamma T = T\frac{dS_N}{dT}$$

$$\rightarrow S_N = \gamma T$$

$$S_S < S_N$$



$$F_N = U - TS = U - \gamma T^2$$

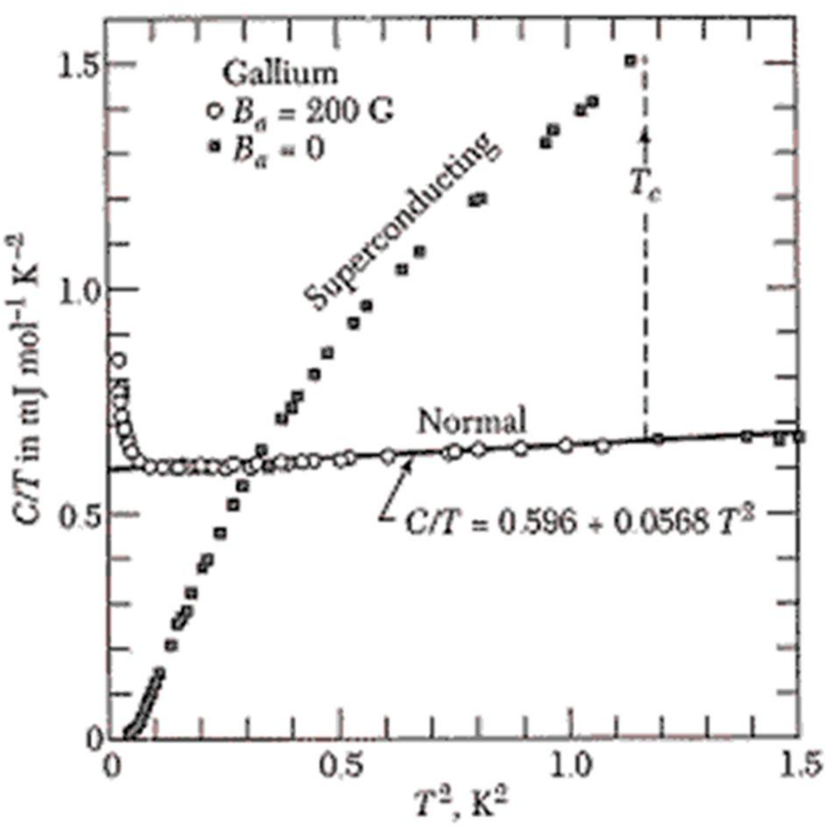


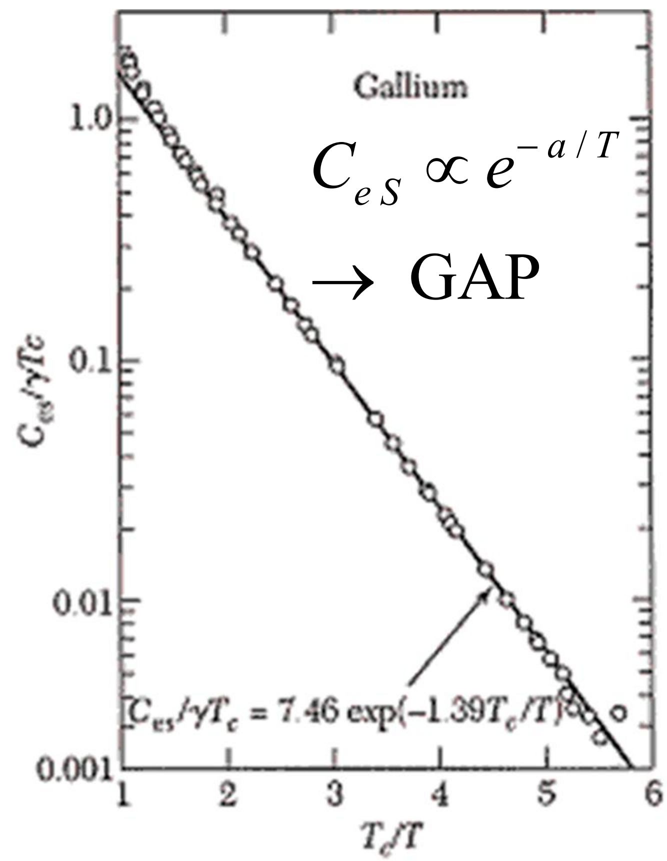
Since less entropy: SC state more ordered !!

What orders ???

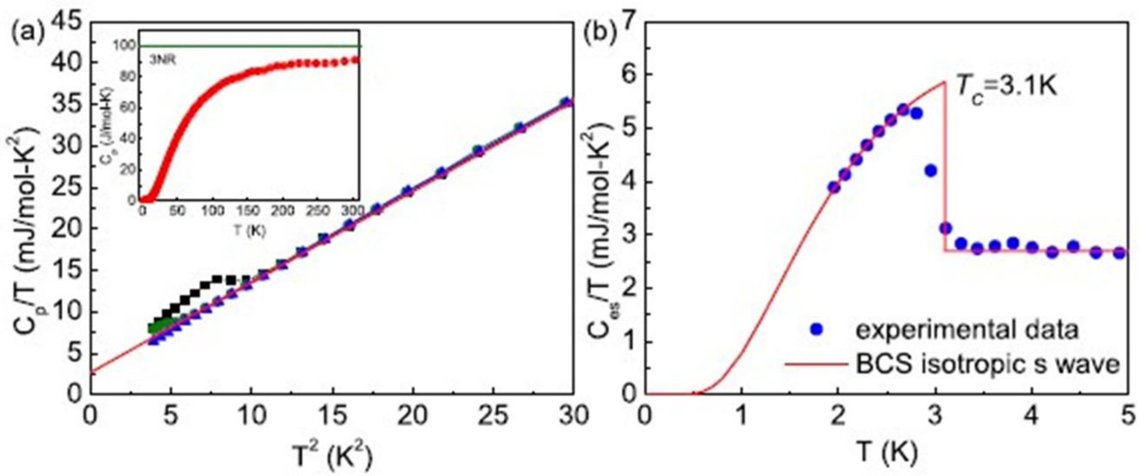
$\Delta S \sim 10^{-4}\, k_B$ per atom
$\rightarrow$ only 10^{-4} e's participate in transition.

Heat capacity → energy gap





Type II specific heat



(a) Low-temperature specific-heat behavior of $Ni_{0.05}ZrTe_3$ plotted as C_p/T *vs.* T at H = 0, 1 and 50 kOe. The solid line is a fit described in the text. Inset: temperature dependence of $C_p(T)$ from 1.95 K to 300 K at H = 0 kOe. (b) Temperature dependence of the electronic specific heat plotted as C_{es}/T *vs.* T at H = 0 kOe. The solid line shows fitted result of C_{es}/T assuming an isotropic *s*-wave BCS gap. [Lei et al. 2011]

Superconducting gap

Tunneling (Giaever et al., 1961)

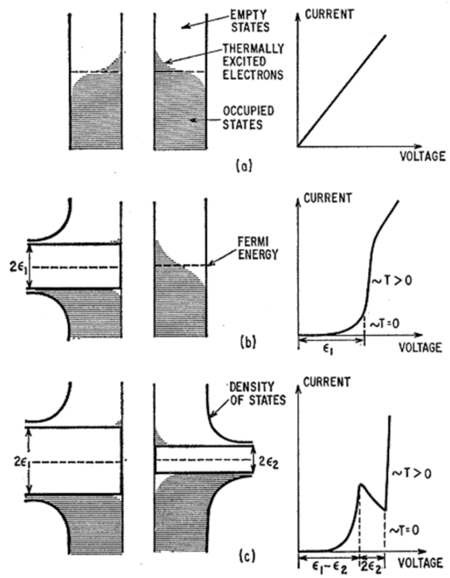


FIG. 4. Energy diagram displaying the density of states and the current-voltage characteristics for the three cases. (a) Both metals in the normal state. (b) One metal in the normal state and one in the superconducting state. (c) Both metals in the superconducting state.

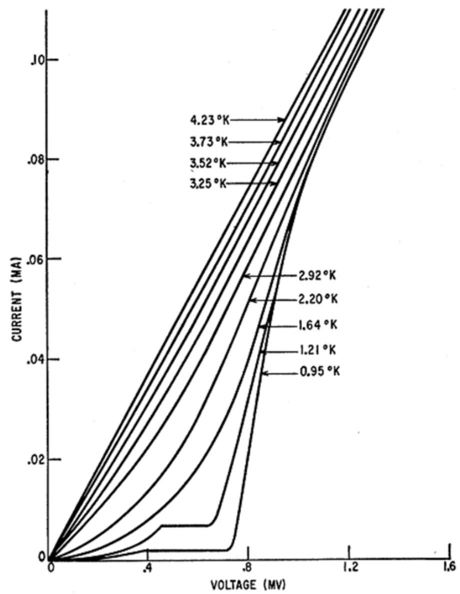


FIG. 6. Current-voltage characteristics of an Al-Al_2O_3-Sn sandwich at various temperatures.

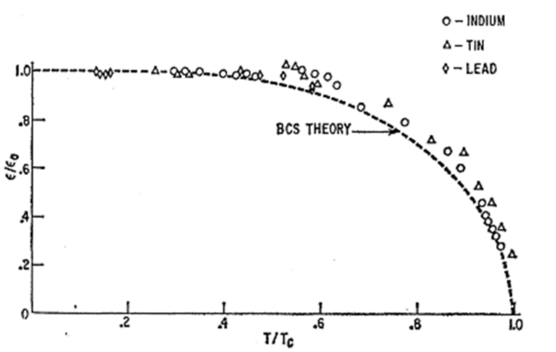


FIG. 11. The energy gap of Pb, Sn, and In films as a function of reduced temperature, compared with the Bardeen-Cooper-Schrieffer theory.

Optics (Hwang et al., 2007)

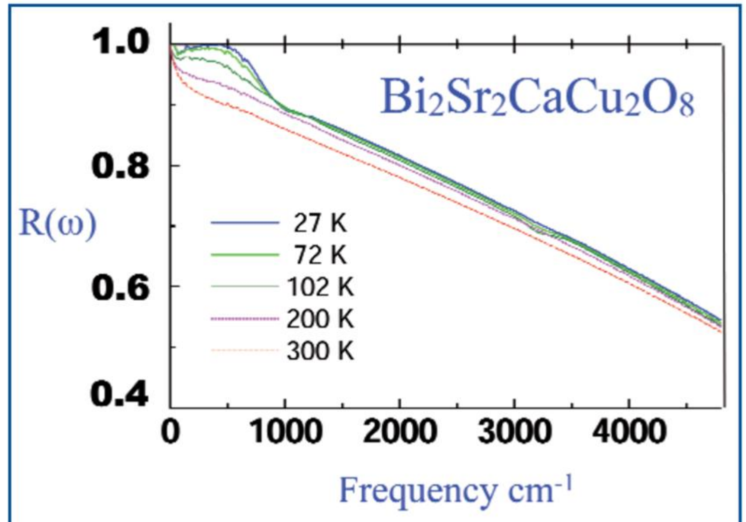


Fig. 2 (color online):The reflectance of a high temperature superconductor with $T_c = 91$ K at various temperatures from Hwang *et al* [13] Note the sharp onset of absorption at 27 K in the superconducting state, above a frequency of 500 cm^{-1}. In this clean limit superconductor the onset marks the energy where the incoming photon can break a Cooper pair and generate a bosonic excitation.

Isotope effect

Table I. Experimental and Calculated Infrared Absorption Bands for $^{12}C_{60}$ and $^{13}C_{60}$

	frequency (cm^{-1})			
$^{12}C_{60}$ (exptl)	1429	1183	576	527
$^{13}C_{60}$ (calcd[a])	1373	1137	553	506
$^{13}C_{60}$ (exptl)	1375	1138	554	506

[a] Calculated from the $^{12}C_{60}$ experimental data using $\nu(^{13}C_{60}) = \nu(^{12}C_{60})[M(^{12}C)/M(^{13}C)]^{1/2}$. IR spectra were recorded on C_{60} thin films using a Nicolet-5PC FT-IR.

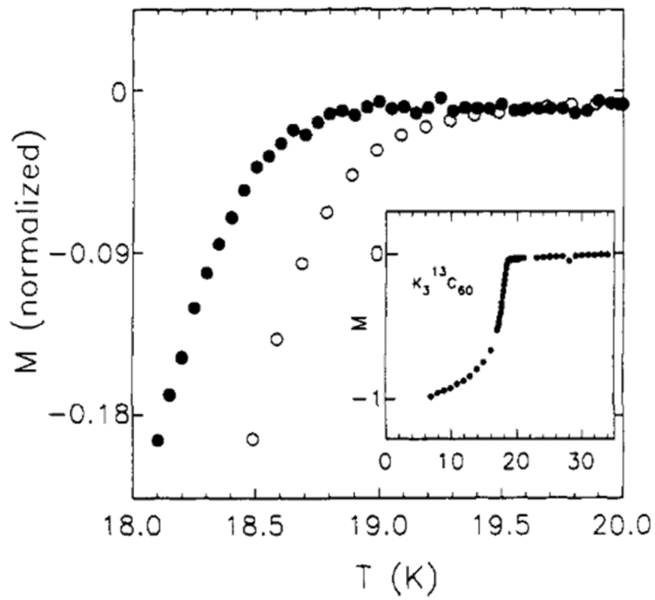


Figure 2. High-resolution temperature-dependent magnetization measurements obtained on $K_3{}^{13}C_{60}$ (●) and $K_3{}^{12}C_{60}$ (○) samples highlighting the depression in T_c for the isotopically substituted material. The samples were initially cooled in zero field to 5 K, and then the curves were recorded on warming in a field of 20 Oe. The curves were normalized to the value of the magnetization at 5 K. The inset shows a full magnetization curve for a $K_3{}^{13}C_{60}$ sample.

J. Am. Chem. Soc. **1992**, *114*, 3141–3142

Synthesis of Pure $^{13}C_{60}$ and Determination of the Isotope Effect for Fullerene Superconductors

Chia-Chun Chen and Charles M. Lieber*

Flux quantization

VOLUME 7, NUMBER 2 PHYSICAL REVIEW LETTERS JULY 15, 1961

EXPERIMENTAL EVIDENCE FOR QUANTIZED FLUX IN SUPERCONDUCTING CYLINDERS*

Bascom S. Deaver, Jr., and William M. Fairbank
Department of Physics, Stanford University, Stanford, California
(Received June 16, 1961)

We have observed experimentally quantized values of magnetic flux trapped in hollow superconducting cylinders. That such an effect might occur was originally suggested by London[1] and Onsager,[2] the predicted unit being hc/e. The quantized unit we find experimentally is not hc/e, but $hc/2e$ within experimental error.[3]

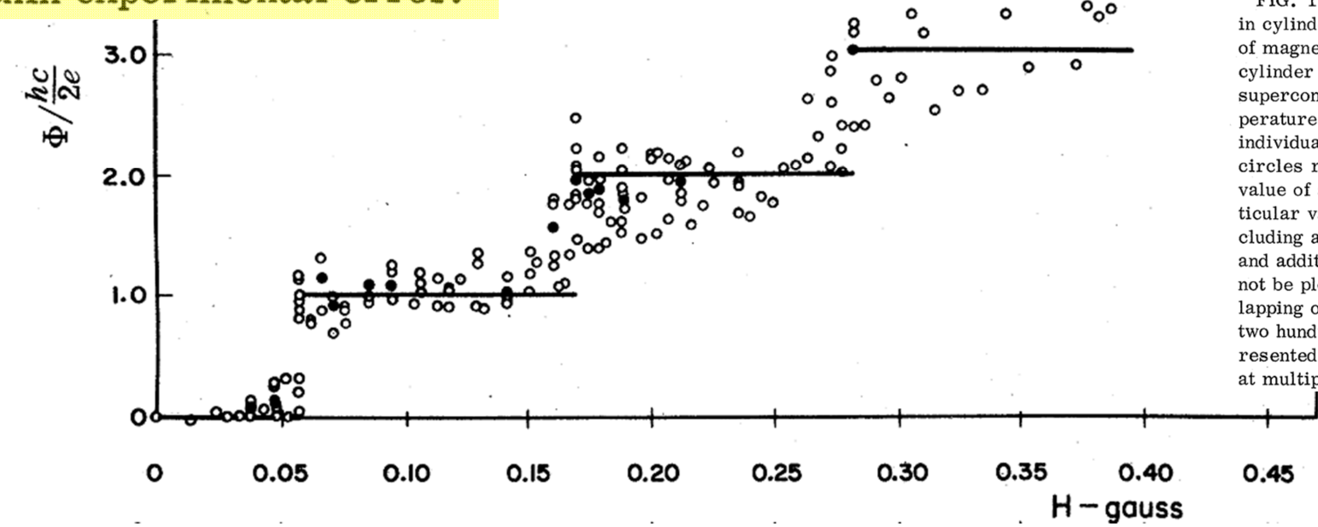


FIG. 1. (Upper) Trapped flux in cylinder No. 1 as a function of magnetic field in which the cylinder was cooled below the superconducting transition temperature. The open circles are individual data points. The solid circles represent the average value of all data points at a particular value of applied field including all the points plotted and additional data which could not be plotted due to severe overlapping of points. Approximately two hundred data points are represented. The lines are drawn at multiples of $hc/2e$. (Lower)