A dream of room-temperature superconductors

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Outline

1. Room-temperature ambient-pressure superconductor ~ the "Holy Grail" of science!

~Room temperature superconductor LK-99?

2. Introduction to Superconductivity:

a. Characteristics of superconductors

b. Development history

~The low-T_c and high-T_c superconductors

~Searching for new superconductors?

c. Applications of superconductors

3. Verify LK-99

~Magnetic and electrical measurements

4. Summary

Room-temperature ambient-pressure superconductors :

~ LK-99: A room-temperature superconductor?

On July 27, 2023, a Korean research team announced the discovery of a room-temperature ambient-pressure superconductor: LK-99 (chemical formula $Pb_9Cu(PO_4)_6O$, a lead-copper apatite), which exhibited superconducting properties at 127°C !

arxiv.org/abs/2307.12008

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Condensed Matter > Superconductivity

[Submitted on 22 Jul 2023]

The First Room-Temperature Ambient-Pressur

Sukbae Lee, Ji-Hoon Kim, Young-Wan Kwon

For the first time in the world, we succeeded in synthesizing the room-temperature modified lead-apatite (LK-99) structure. The superconductivity of LK-99 is proved w magnetic field (H_c), and the Meissner effect. The superconductivity of LK-99 origin not by external factors such as temperature and pressure. The shrinkage is caused phosphate and it generates the stress. It concurrently transfers to Pb(1) of the cylir creates superconducting quantum wells (SQWs) in the interface. The heat capacity superconductivity of LK-99. The unique structure of LK-99 that allows the minute d factor that LK-99 maintains and exhibits superconductivity at room temperatures a

Subjects: Superconductivity (cond-mat.supr-con)

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(or arXiv:2307.12008v1 [cond-mat.supr-con] for this version)

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[Submitted on 22 Jul 2023 (v1), last revised 11 Aug 2023 (this version, v3)]

Superconductor $Pb_{10-x}Cu_x(PO_4)_6O$ showing levitation at room temperature and atmospheric pressure and mechanism

Sukbae Lee, Jihoon Kim, Hyun-Tak Kim, Sungyeon Im, SooMin An, Keun Ho Auh

A material called LK-99, a modified-lead apatite crystal structure with the composition $Pb_{10-x}Cu_x(PO_4)_6O$ $(0.9 < x < 1.1)$, has been synthesized using the solid-state method. The material exhibits the Ohmic metal characteristic of Pb(6s1) above its superconducting critical temperature, T_c, and the levitation phenomenon as Meissner effect of a superconductor at room temperature and atmospheric pressure below T_c. A LK-99 sample shows T_c above 126.85°C (400 K). We analyze that the possibility of room-temperature superconductivity in this material is attributed to two factors: the first being the volume contraction resulting from an insulator-metal transition achieved by substituting Pb with Cu, and the second being on-site repulsive Coulomb interaction enhanced by the structural deformation in the one-dimensional(D) chain (Cu^{2+}-$O_{1/2}$-Cu^{2+} along the c-axis) structure owing to superconducting condensation at T_c. The mechanism of the room-temperature T_c is discussed by 1-D BR-BCS theory.

Comments: 18 pages, 7 figures

Subjects: Superconductivity (cond-mat.supr-con)

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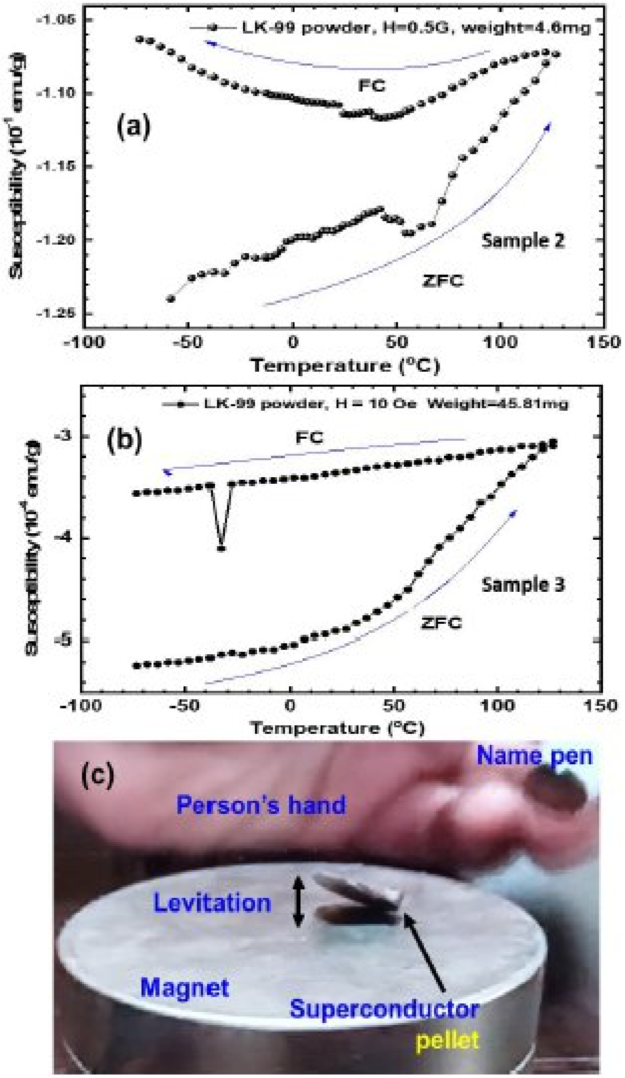
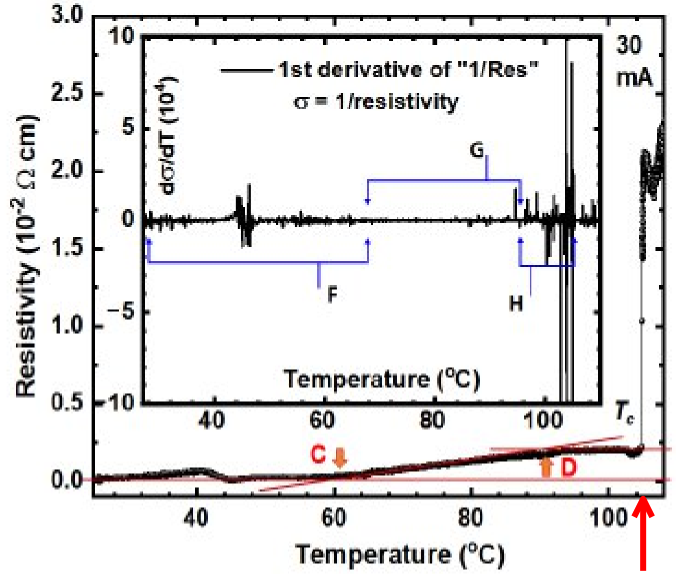
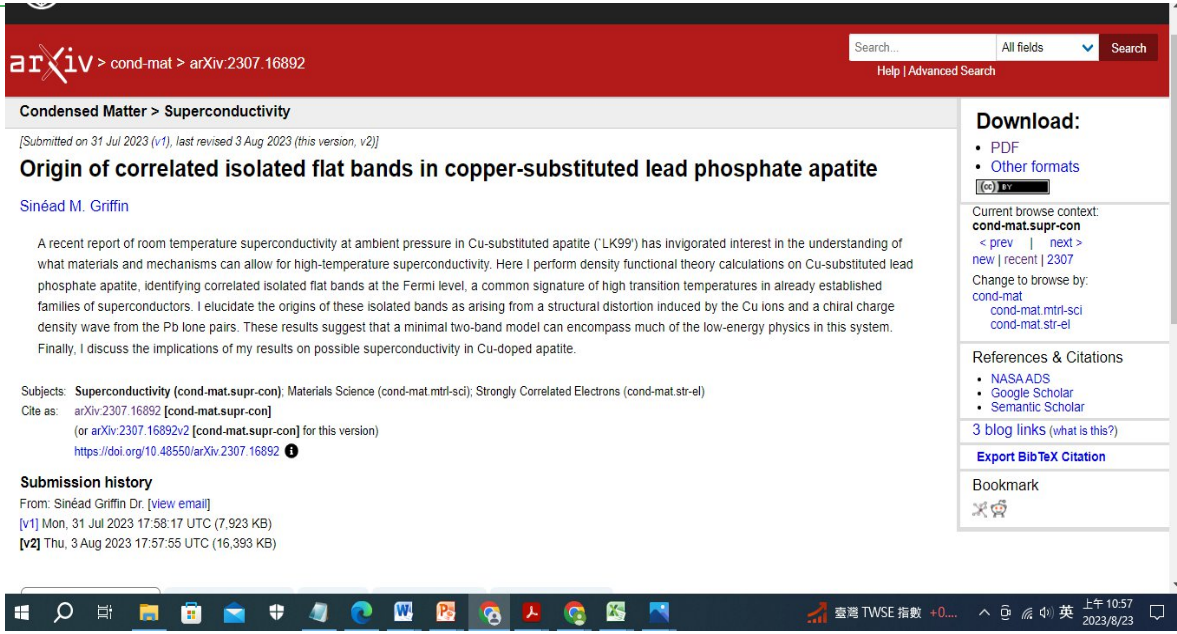




378 K
(105℃)

Magnetic and electrical measurements on LK-99:

Diamagnetic-like & zero-resistance-like superconductor!!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Condensed Matter > Superconductivity

[Submitted on 31 Jul 2023 (v1), last revised 3 Aug 2023 (this version, v2)]

Origin of correlated isolated flat bands in copper-substituted lead phosphate apatite

Sinéad M. Griffin

A recent report of room temperature superconductivity at ambient pressure in Cu-substituted apatite ('LK99') has invigorated interest in the understanding of what materials and mechanisms can allow for high-temperature superconductivity. Here I perform density functional theory calculations on Cu-substituted lead phosphate apatite, identifying correlated isolated flat bands at the Fermi level, a common signature of high transition temperatures in already established families of superconductors. I elucidate the origins of these isolated bands as arising from a structural distortion induced by the Cu ions and a chiral charge density wave from the Pb lone pairs. These results suggest that a minimal two-band model can encompass much of the low-energy physics in this system. Finally, I discuss the implications of my results on possible superconductivity in Cu-doped apatite.

Subjects: **Superconductivity (cond-mat.supr-con)**; Materials Science (cond-mat.mtrl-sci); Strongly Correlated Electrons (cond-mat.str-el)

Cite as: arXiv:2307.16892 **[cond-mat.supr-con]**

(or arXiv:2307.16892v2 **[cond-mat.supr-con]** for this version)

https://doi.org/10.48550/arXiv.2307.16892

Submission history

From: Sinéad Griffin Dr. [view email]

[v1] Mon, 31 Jul 2023 17:58:17 UTC (7,923 KB)

[v2] Thu, 3 Aug 2023 17:57:55 UTC (16,393 KB)

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References & Citations

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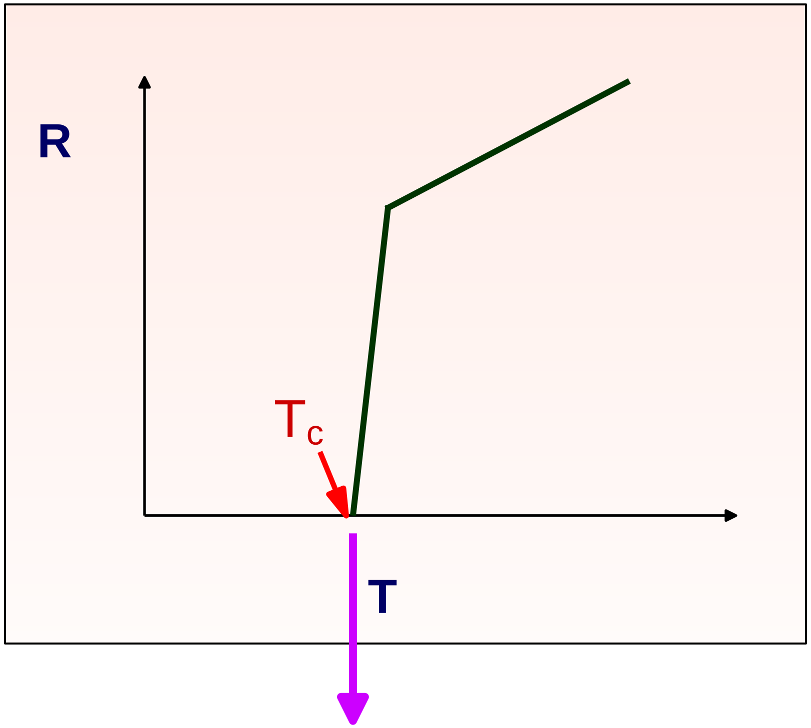
- On August 1, another article showed that LK-99 can be a superconductor via proper copper doping ✉ the first paper to prove the feasibility of the "LK-99" by theory.
- Driving superconductor concept stocks to sharp rise (American Superconductor AMSC, lead & copper futures, conductive wire materials, medical, etc.)!

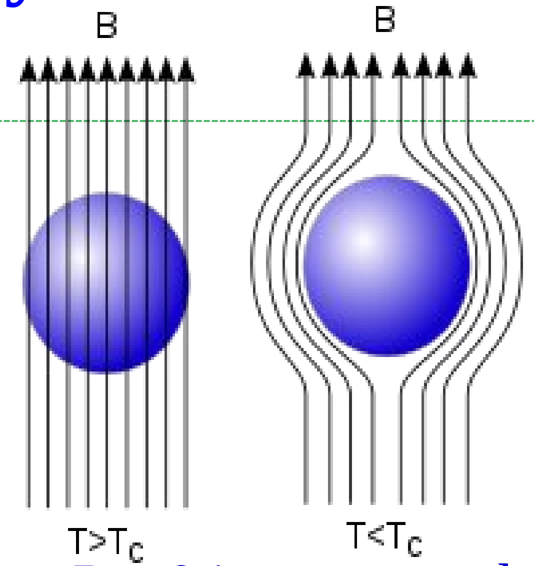
- Room-temperature ambient-pressure superconductor ~ the "Holy Grail" of science~LK-99 ?

Introduction to superconductivity:

- Characteristics of superconductor:

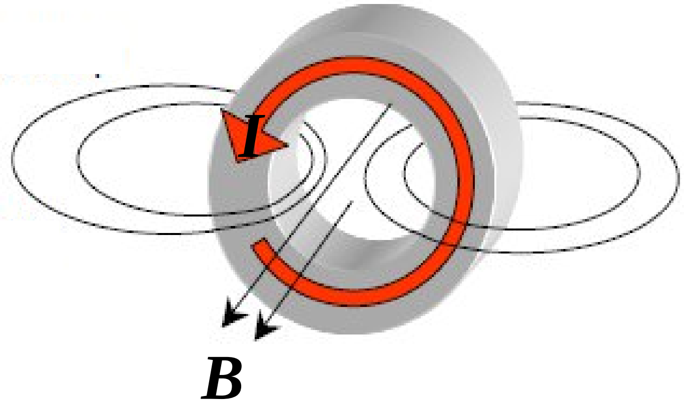


Zero resistance!



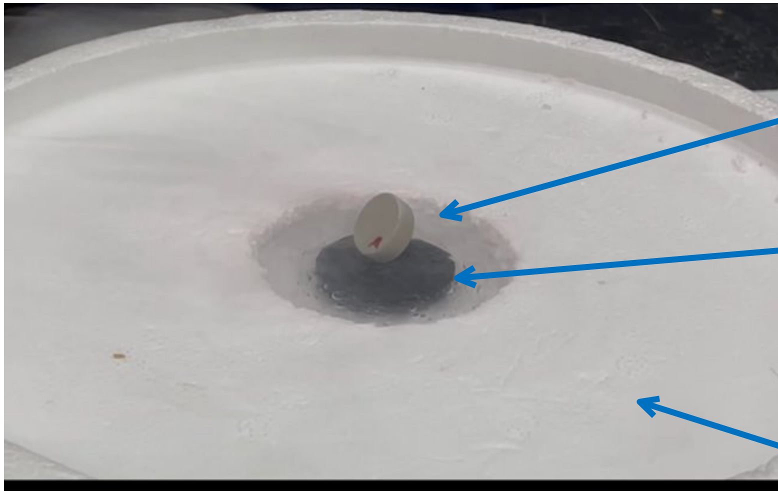
Meissner effect: $B = 0$ in superconductors

~Perfect diamagnetism !



Persistent Current* (>10^5 years)*!

A Nobel-Prize Experiment you can do:



Magnet

釔鋇銅氧（$YBa_2Cu_3O_y$, YBCO）superconductor

Liquid N_2

Magnetic levitation

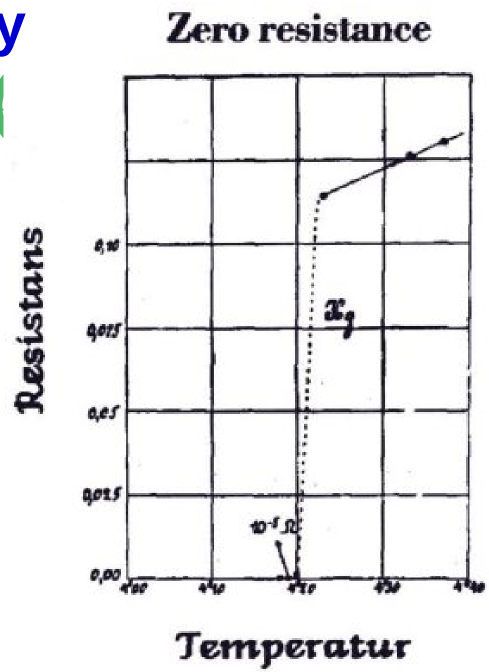
Magnetic levitation

Discovery of Superconductivity

- Discovered by Kamerlingh Onnes in 1911 during first low temperature measurements to liquefy helium.

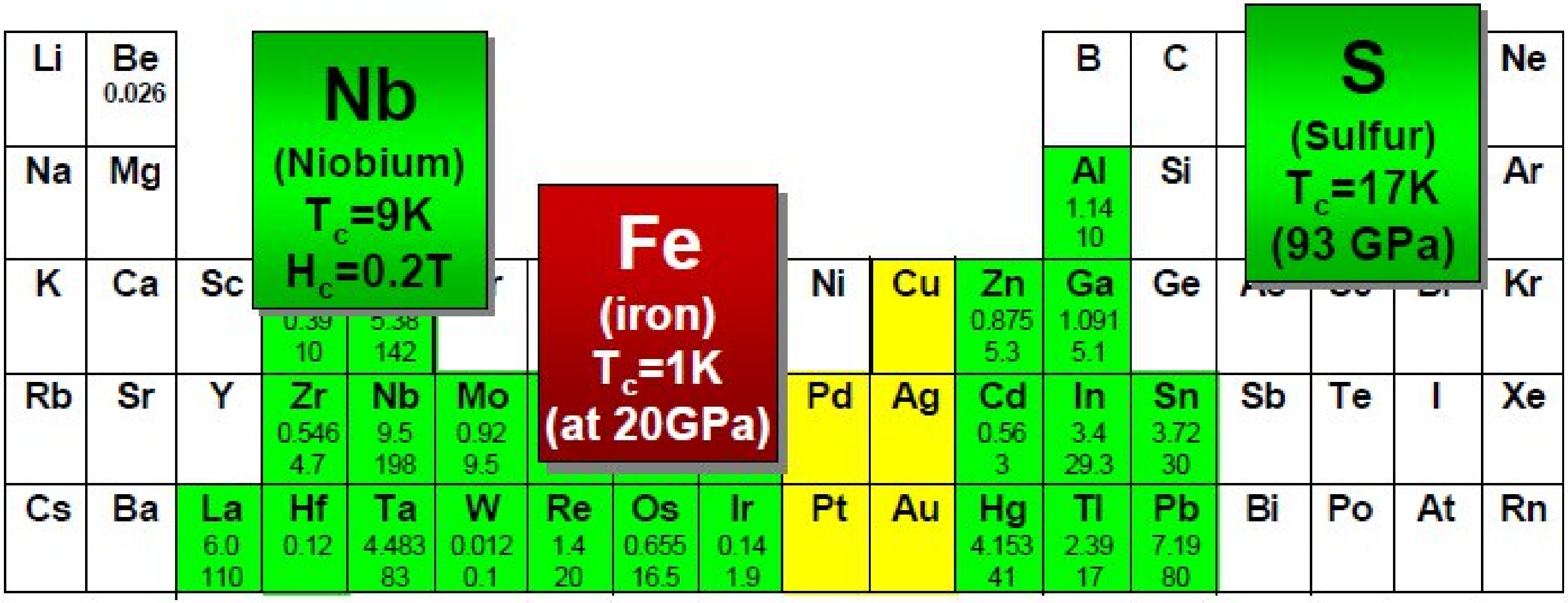
- Whilst measuring the resistivity of "pure" mercury (Hg) he noticed that the electrical resistance dropped to zero at 4.2 K .

- In 1912 he found that the resistive state is restored in a magnetic field or at high transport currents.



H. Kamerlingh Onnes
(歐尼斯)
1913 Nobel Prize in Physics

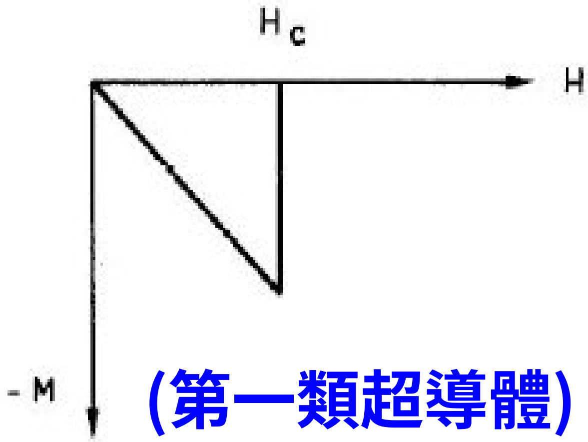
Superconductivity



- Transition temperatures (K) and critical fields are generally low
- Metals with the highest conductivities are not superconductors
- The magnetic 3d elements are not superconducting

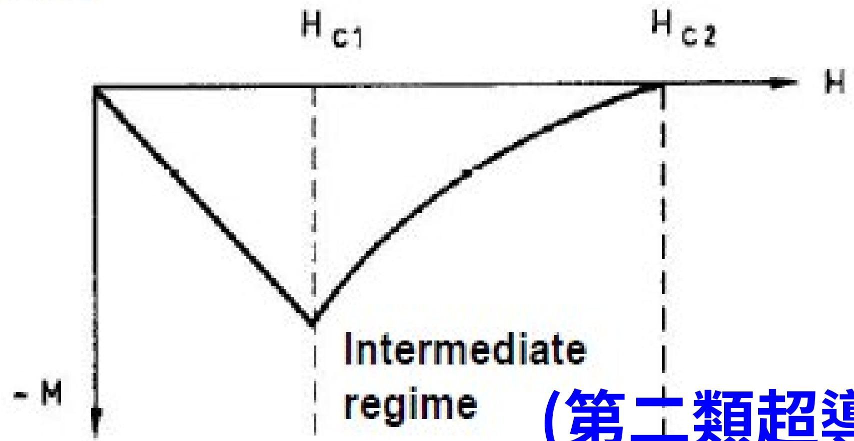
Superconductivity – Phenomena and facts

Hard and soft superconductors



(第一類超導體)

Soft (type I) superconductor

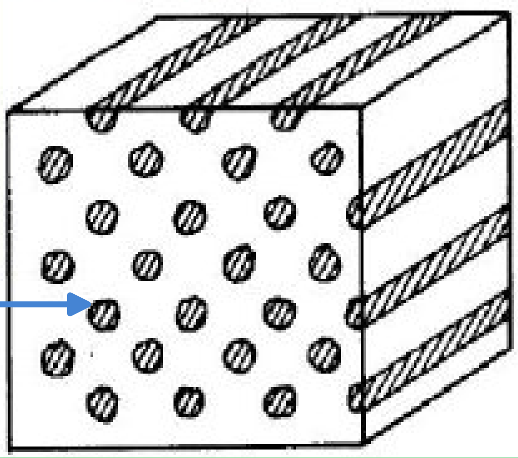


(第二類超導體)

Hard (type II) superconductor shows incomplete Meissner effect (higher current possible

Inside a superconductor a magnetization –M (opposed to the outside magnetization +M) is built up Above a critical field (electrical current) current this magnetization collapses and superconductivity ceases

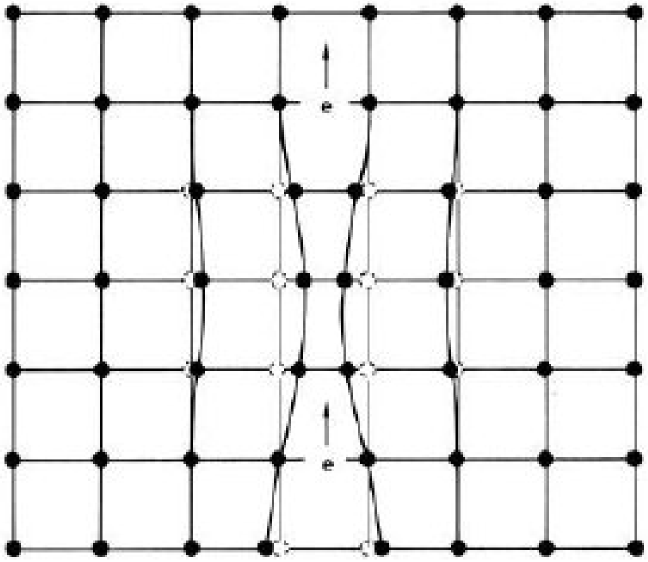
Magnetic flux trapped by defects or impurities



Normal and superconducting regions in a type II superconductor

A theory of superconductivity – the BCS model

1972 **Nobel Prize in Physics**



An electron travelling through the lattice polarizes its surrounding

Electron fast – lattice vibrations slow

⇒ a second electron is drawn into the positive trough produced by the first electron

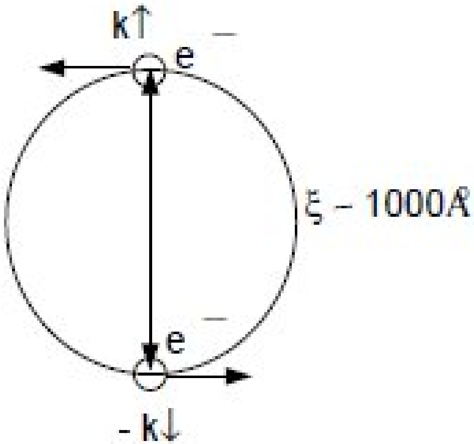
⇒ electron movements are coupled electron are highly correlated

⇒ **Cooper pairs**

(古柏對~電子對)

maximum deformation at a time $\tau \sim \frac{2\pi}{\omega_D} \sim 10^{-13}\mathrm{s}$

$$\sim v_F \tau \sim 10^8 \frac{\mathrm{cm}}{\mathrm{s}} \cdot 10^{-13}\mathrm{s} \sim 1000\ \mathring{A}.$$

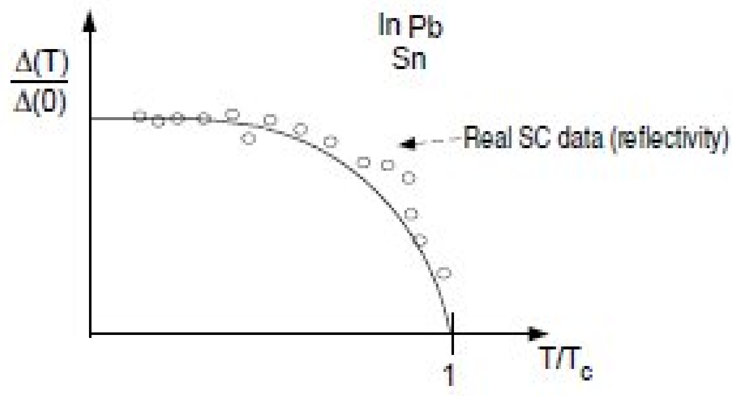


obey the Pauli principle

~ Phonon-mediated Cooper pairs! & T_c < 40 K!

Consequences of BCS and experiments:

- Energy gap:
  (超導能隙)



The conduction band of a superconductor exhibits a superconducting gap

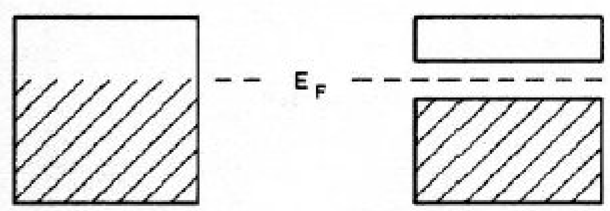


Figure 19: *The evolution of the gap (as measured by reflectivity) as a function of temperature. The BCS approximation is in reasonably good agreement with experiment.*

2. Isotope effect:
(同位素效應)

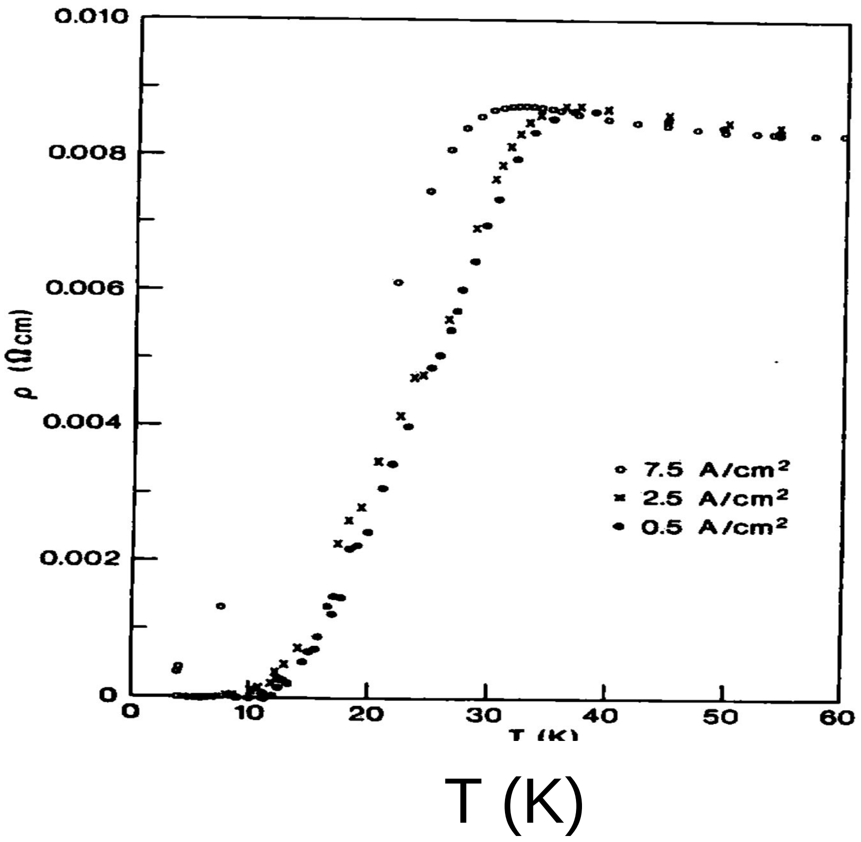
$$\omega_D \sim \sqrt{\frac{k}{M}} \sim M^{-\frac{1}{2}}.$$

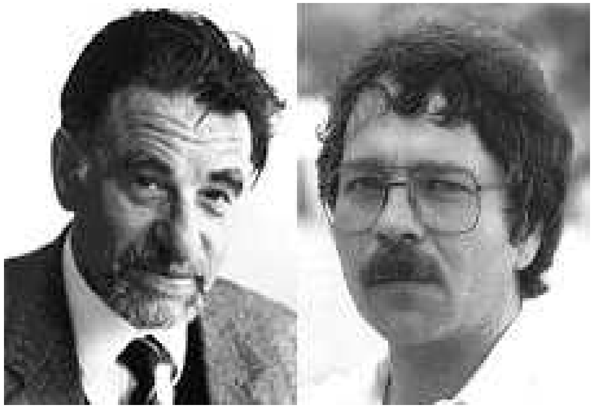
$$T_c \propto \sqrt{\frac{1}{M}}$$

~ **All these observation are accounted for by the BCS theory**

~ Sound-like perfect both in theory and experiment!

~The generation of high-T_c superconductors (1986):

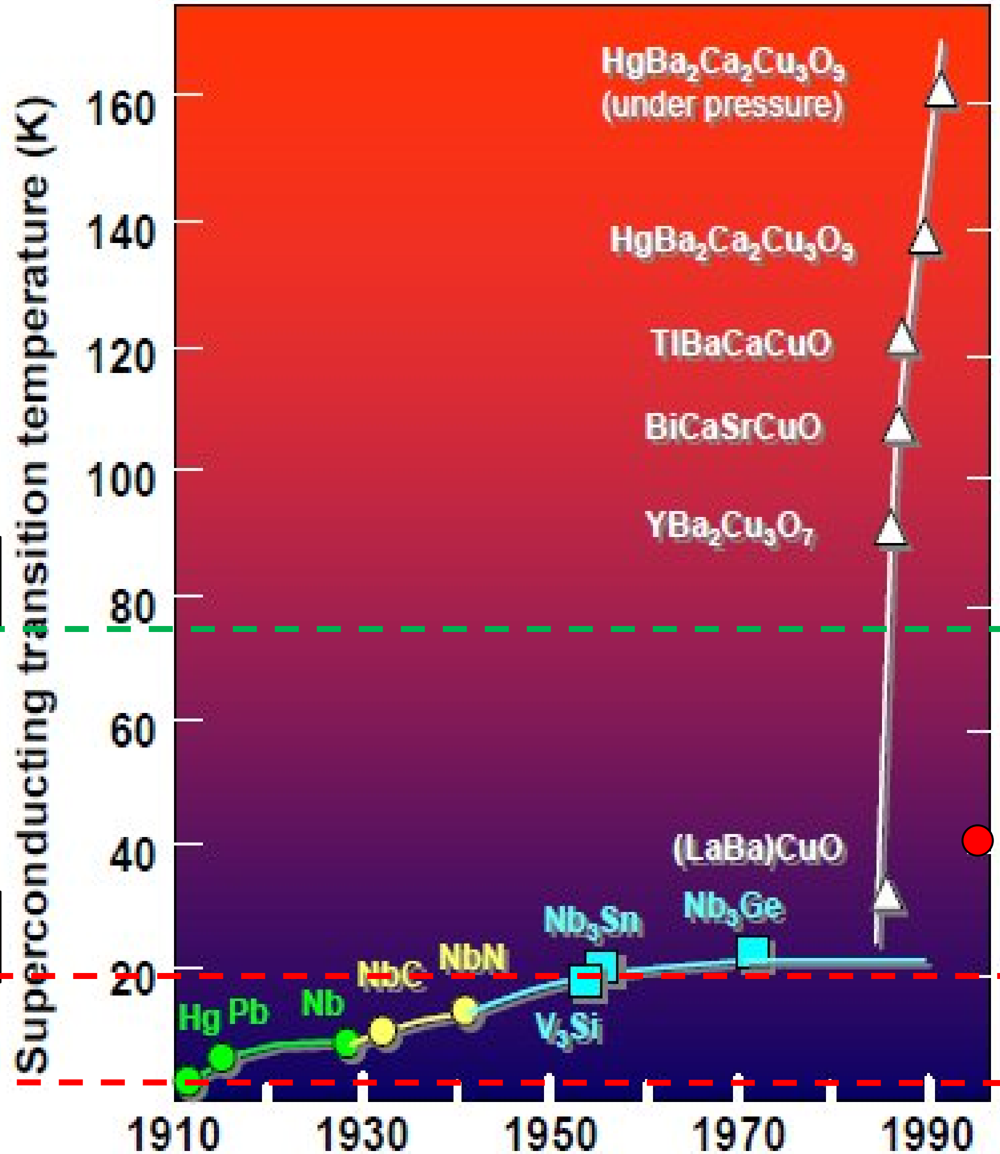




1987 Nobel Prize in Physics

Bednorz & Muller discovered the La-Ba-Cu-O superconductor with T_c ~30 K

Since the discovery of superconductors, the transition of T_c



LaH_{10} (250 K @170 GPa, 2019)

H_2S (203 K @150 GPa, 2015)

Highest T_c under normal pressure: ~135 K

$RFeAsO_xF_y$ (56 K, 2008)

MgB_2(39 K, 2001)

Liquid nitrogen

Liquid hydrogen

Liquid helium

Higher T_c ?

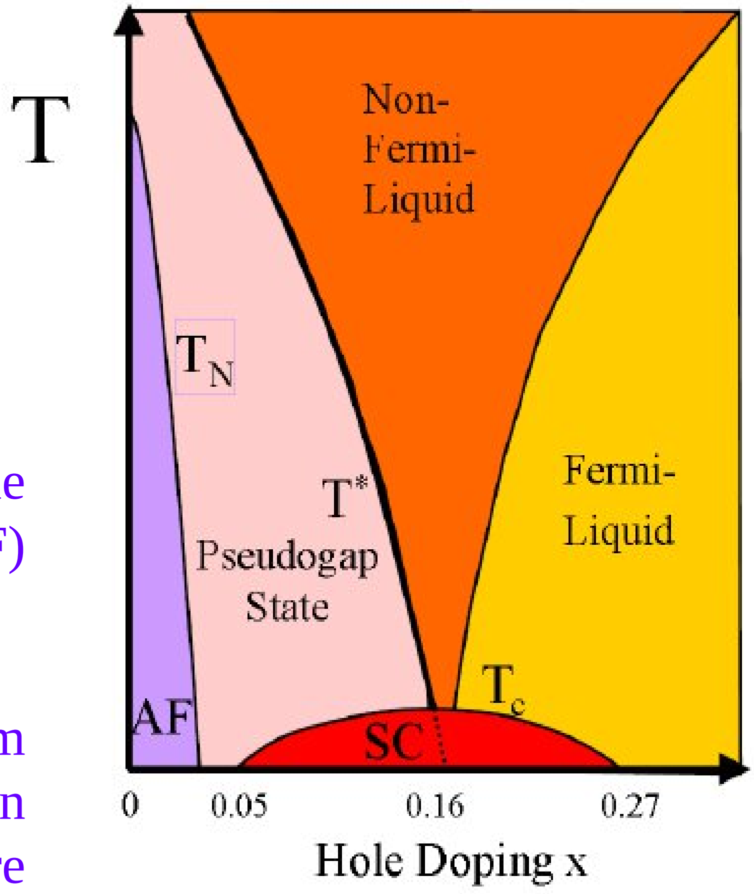
New SCs ?

(Unconventional SCs)

High-T_c superconducting (HTS) cuprates:

1. An unusual isotope effect in a high-transition-temperature superconductor ~ see: *Nature*, Vol. 430, No. 6996. (08 July 2004), pp. 187-190. ■ *not* BCS superconductor!

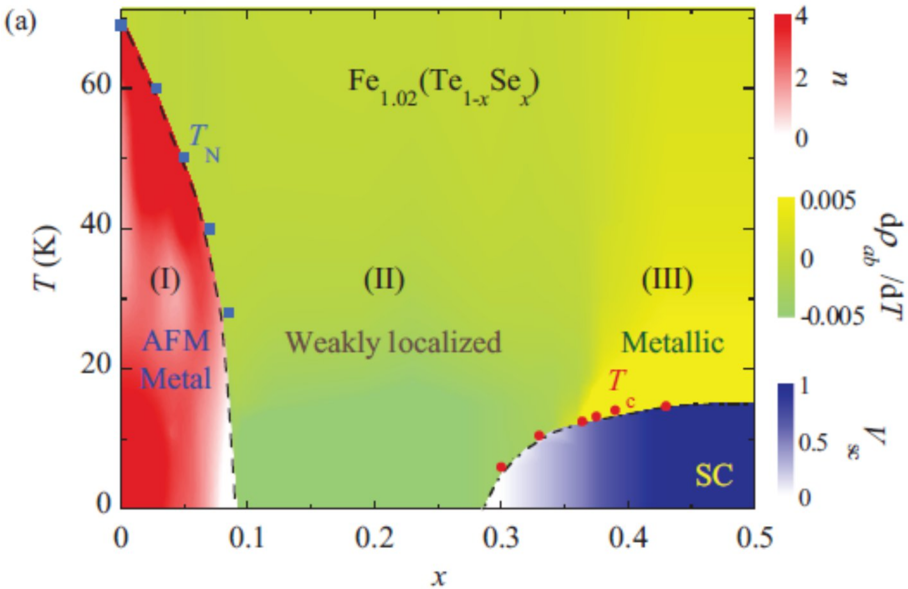
2. Quantum critical point:
~ Spin (quantum) fluctuation mediated :
~see: Philippe Bourges et al., Physical Review Letters (2006, May)

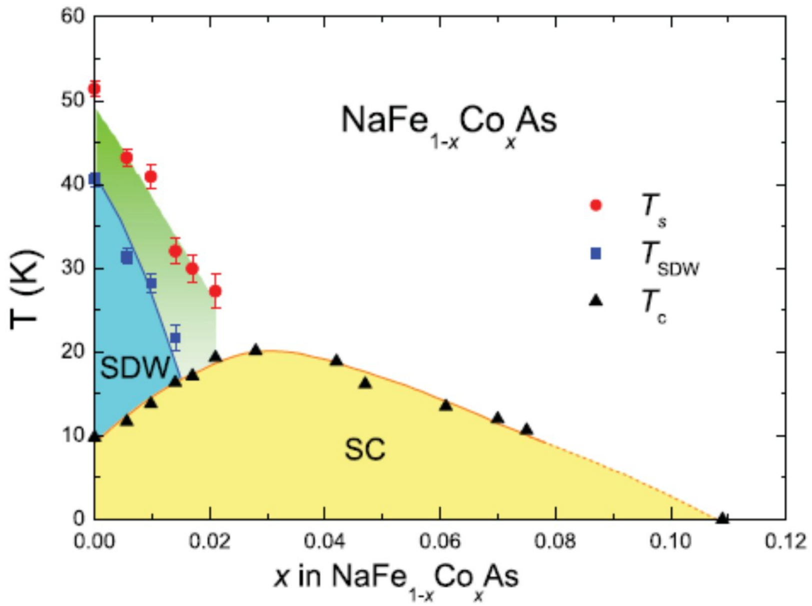


*The parent material ■ through doping some elements ■suppress antiferromagnetic (AF) characteristics ■ superconductivity appear!

*Electron pairs are paired by "quantum fluctuations" as a medium, not by the vibration of lattice atoms (traditional low-temperature superconductors)!■ Strongly coupled pairs!

Iron-based superconductors:





QCP phase diagram of iron-based superconducting $FeTe_{1-x}Se_x$ [1]

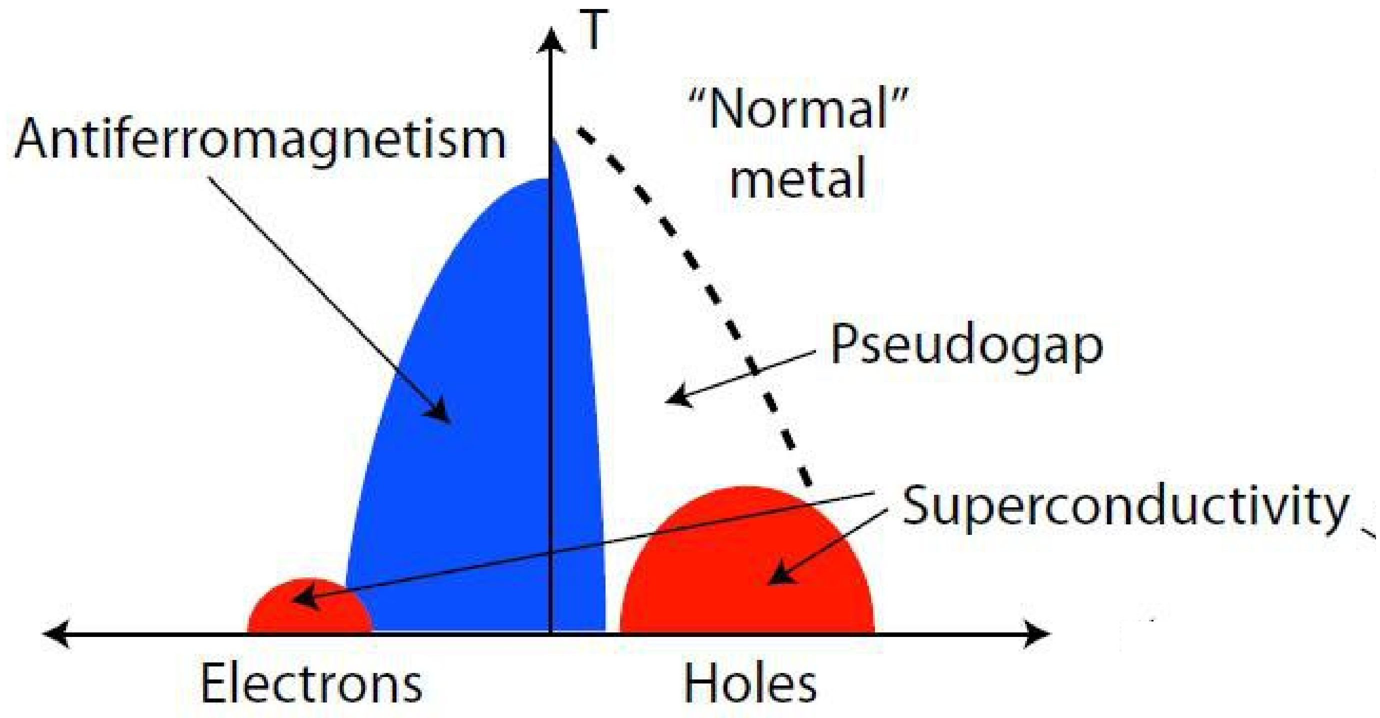
QCP phase diagram of iron-based superconducting $NaFe_{1-x}Co_xAs$ [2]

[1] J. Hu *et al.*, Phys. Rev. B **88**, 094505 (2013).

[2] A. F. Wang *et al.*, Phys. Rev. B **85**, 224521 (2012)

Finding new high-T_c SCs?

~ Search antiferromagnetic materials ~ the parent compound of a new SC!



*The parent material ✉ through doping some elements ✉suppress antiferromagnetic (AF) characteristics ✉ superconductivity appear!

Applications of superconductors:

- in large scale: superconducting magnets, magnetic levitation, magnetic imaging (MRI), high-current electrodes,
- in small scale: superconducting quantum interference devices (SQUIDs), filters, quantum computers, sensors, etc.

中央新幹線

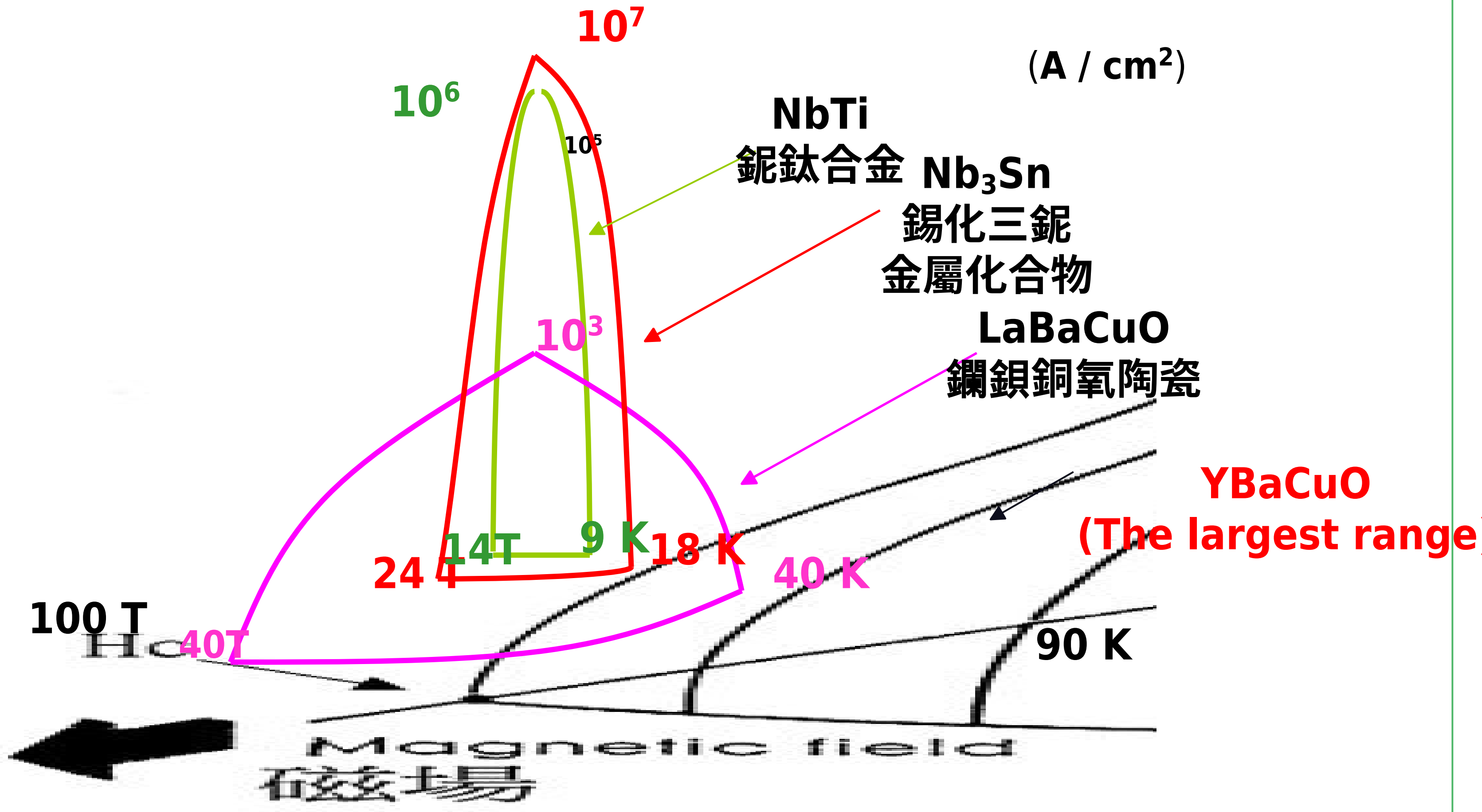
山梨實驗線上試運行的改良型 L0 系 950 番台
（攝於山梨縣笛吹市）

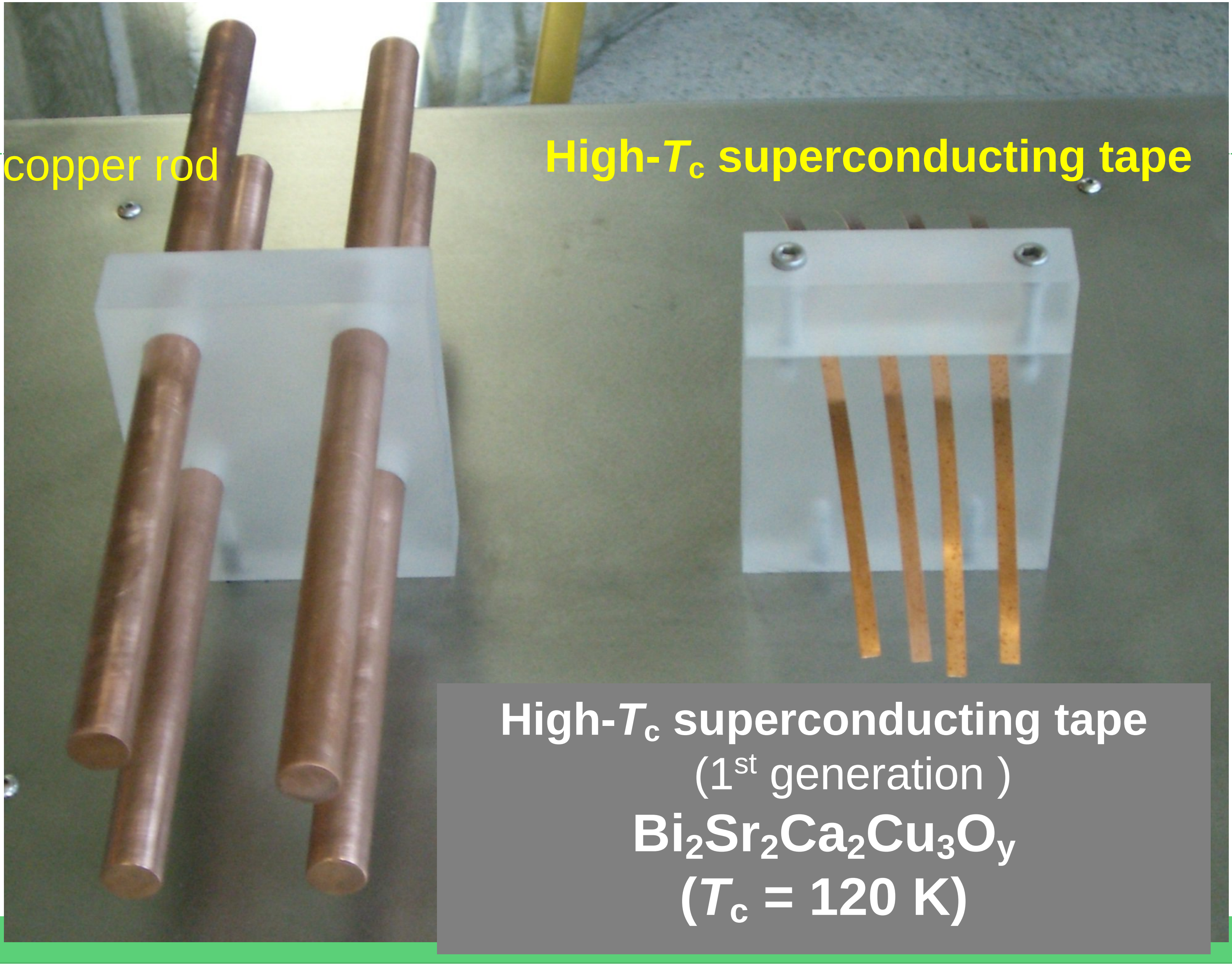
Maglev high-speed railway in Japan:

日本中央新幹線磁浮高速鐵路工程:
2015年4月21日每小時603公里的最高速度;
2020年東京奧運，開放山梨縣車站，讓訪日外賓搭乘、體驗!

https://zh.wikipedia.org/zh-tw/%E4%B8%AD%E5%A4%AE%E6%96%B0%E5%B9%B9%E7%B7%9A

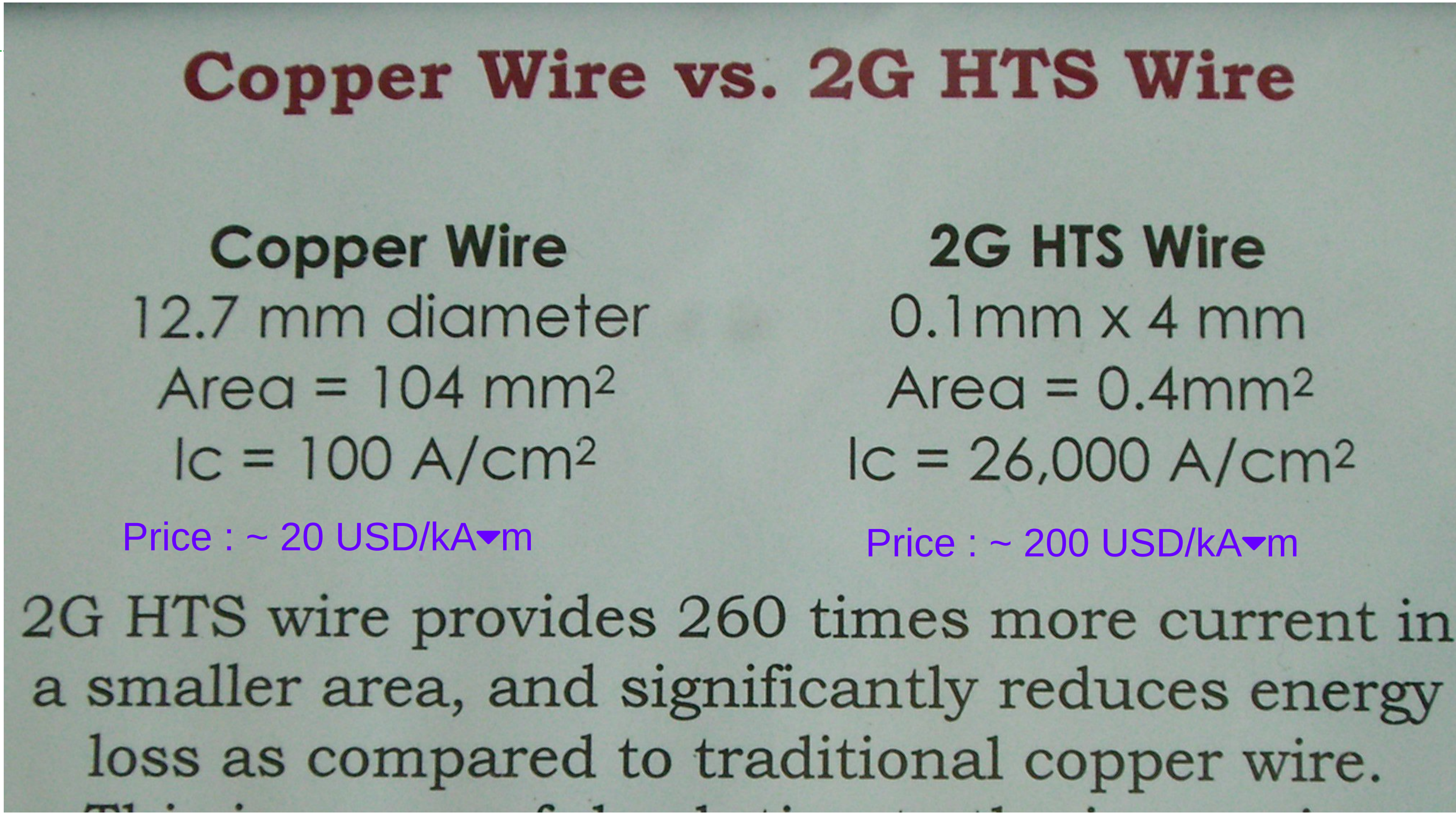
Three limiting factors of superconductors for applications: T_c, H_c, J_c :




copper rod
High-T_c superconducting tape
High-T_c superconducting tape
(1st generation)
$Bi_2Sr_2Ca_2Cu_3O_y$
(T_c = 120 K)

High-T_c superconducting tape (2nd generation)

$YBa_2Cu_3O_y$ (coated on stainless steel tape)

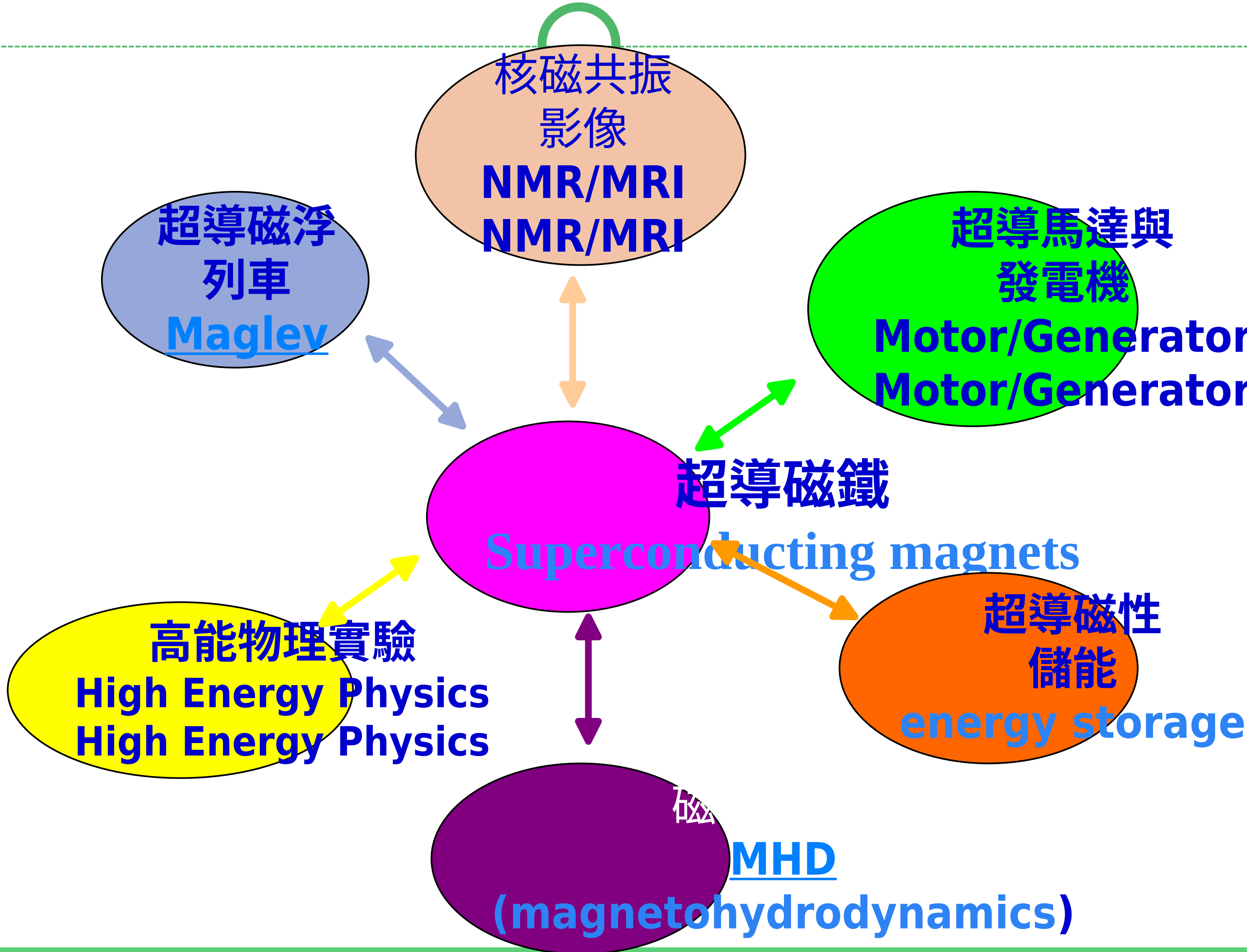


Copper Wire vs. 2G HTS Wire

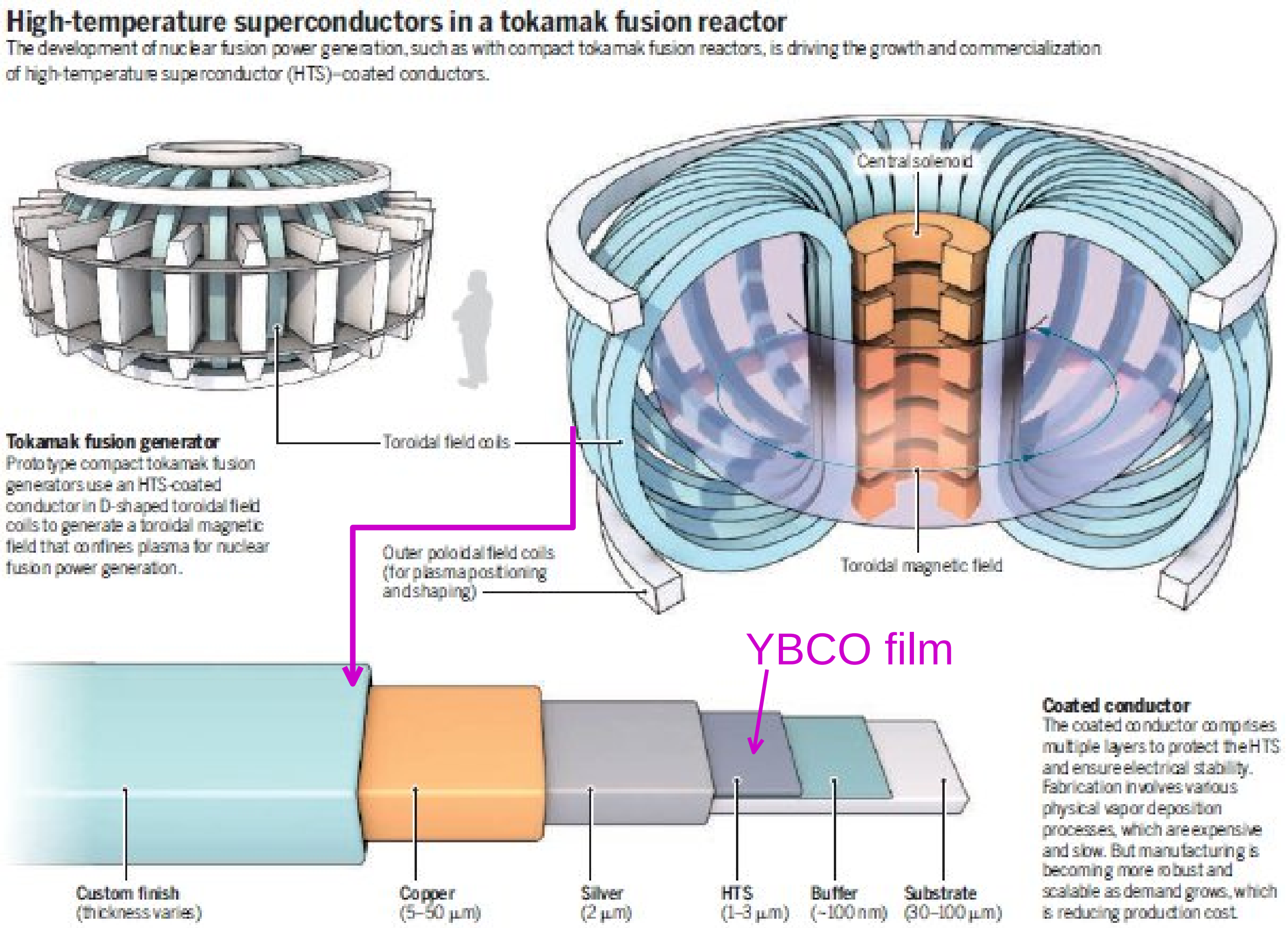
Copper Wire	2G HTS Wire
12.7 mm diameter	0.1mm x 4 mm
Area = 104 mm^2	Area = 0.4mm^2
Ic = 100 A/cm^2	Ic = 26,000 A/cm^2
Price : ~ 20 USD/kA▾m	Price : ~ 200 USD/kA▾m

2G HTS wire provides 260 times more current in a smaller area, and significantly reduces energy loss as compared to traditional copper wire.

Applications of superconducting magnets：



~ 2050 zero-carbon goal?



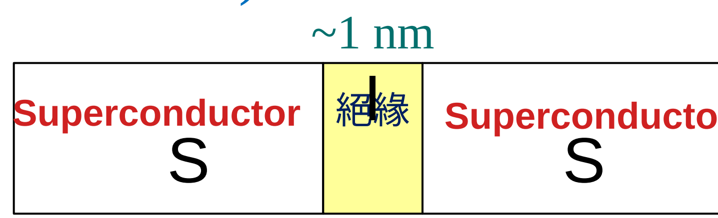
22 JUNE 2023

~ HTS tapes applied to tokamak fusion reactor. (@MIT, USA)

See : SCIENCE Vol 380, Issue 6651 pp. 1220-1222 (2023)

Small-scale application~ ***SQUID Applications:***

(超導量子干涉元件， Superconducting QUantum Interference Device ~**the most sensitive magnetic field sensor!**)



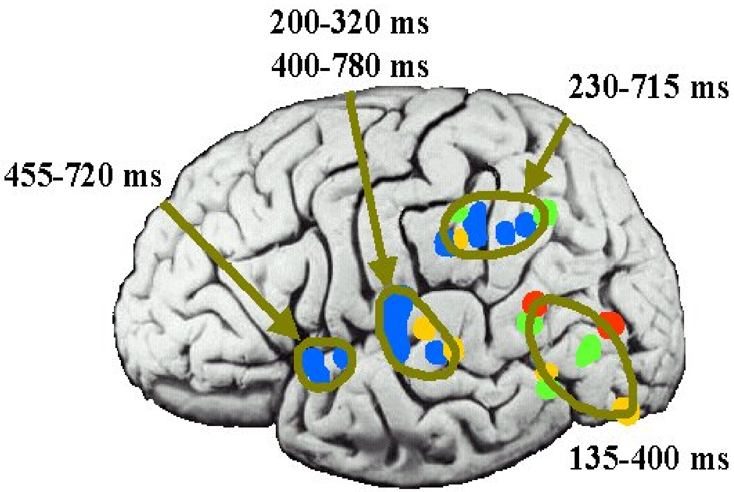
SIS tunneling junction

- ***Biomagnetic Applications*** (生物磁場應用)
- ***Non-Destructive Evaluation*** (***NDE***,非破壞性檢測)
- ***Geophysical Applications*** (地球物理應用)
- ***Scanning SQUID Microscope*** (掃描式**SQUID**顯微鏡)
- ***SQUID NMR and MRI*** (核磁共振及核磁共振影像)

Biomagnetic applications with SQUID

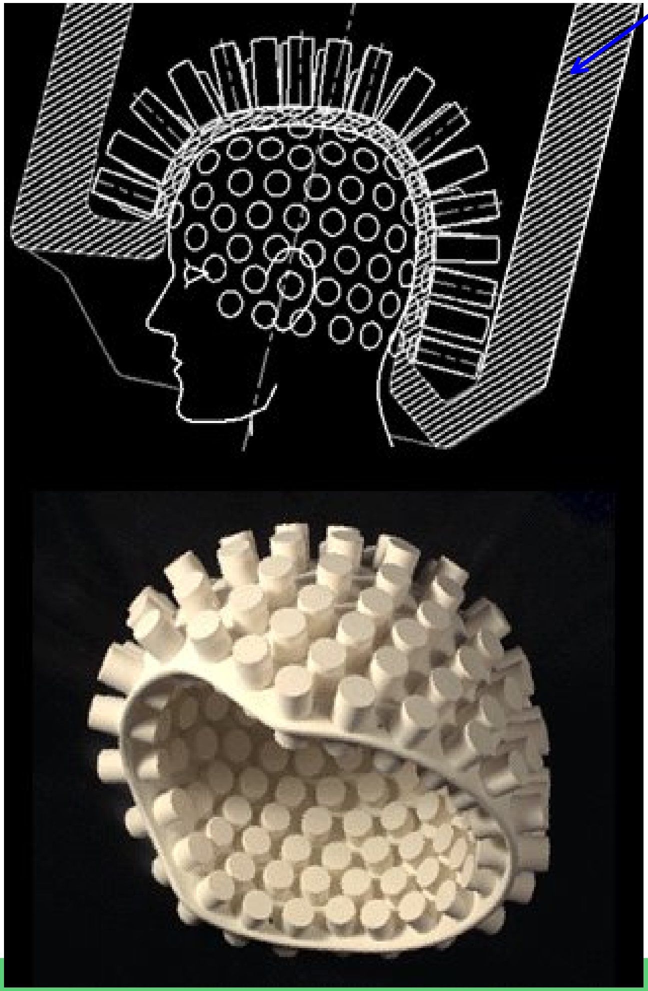
- ***MagnetoEncephaloGraphy (MEG,* 腦磁圖*)***
- ***Liver Susceptometry (LS,* 肝磁導儀*)***
- ***MagnetoCardioGraphy (MCG,* 心磁儀*)***
- ***Magnetic measurement*** *(磁性測量)*

- **MagnetoEncephaloGraphy (MEG)**



Structure of magnetoencephalographic sensing system (CTF Systems Inc., Canada)

Helium Dewar



MEG System in NTU:

Elekta Neuromag MEG System

Commercialized SQUID magnetometer: (@ R110, Department of Physics, NTU)

u**儀器名稱:** 超導量子干涉磁量儀 (SQUID) Magnetometer

u**規格:**美國Quantum Design公司，MPMSR2型

磁場強度：± 7.0 Tesla (± 70000 Gauss)

溫度範圍：2 ~ 400 K (提供2 ~ 360 K服務)

磁矩範圍：5×10^{-7} ~ 300 emu

u**服務項目:**

~ 磁化強度與溫度相依性測量 (*M-T* Curve)。

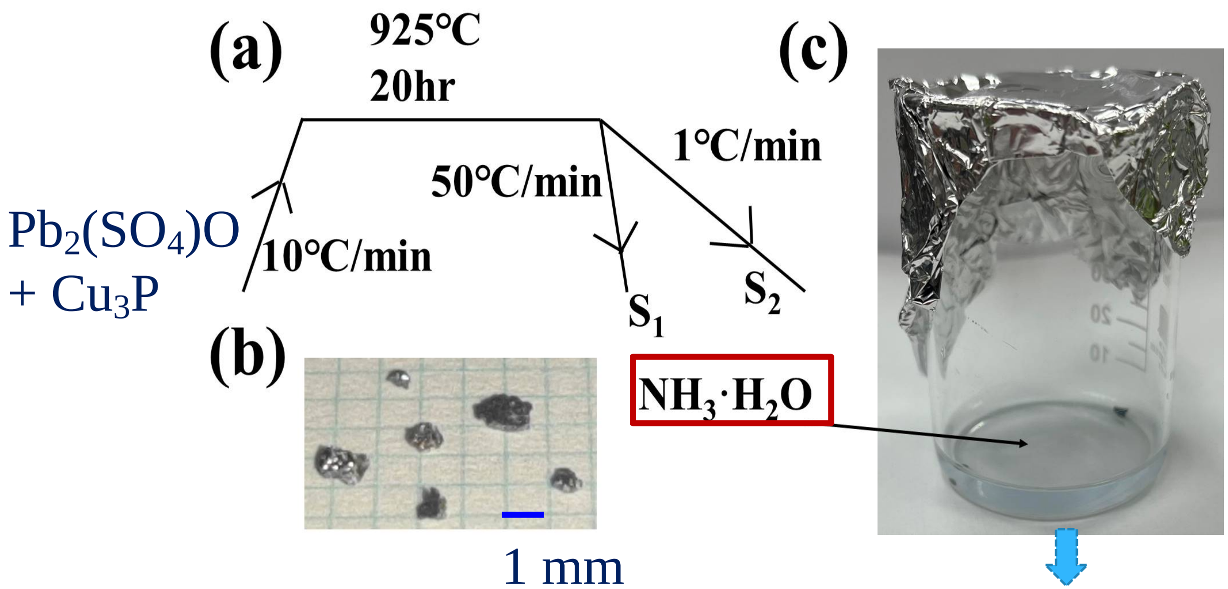
~ 定溫下磁化強度對磁場之相依性/磁滯曲線測量(*M-H* Curve/Hysteresis Loop)。

~ 定磁場及定溫度下之磁化強度測量

u**設置時間: 1989年** (國科會貴儀中心)。

Verify the LK-99 :

~ chemical formula :
$Pb_9Cu(PO_4)_6O$

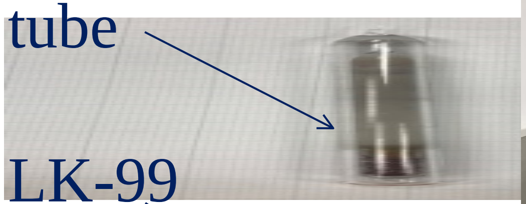


S_1*, S_2*
(Cu_2S-removed)

1 cm

Quartz tube

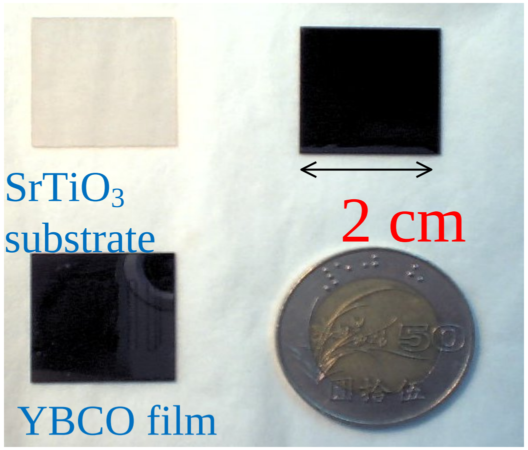
LK-99

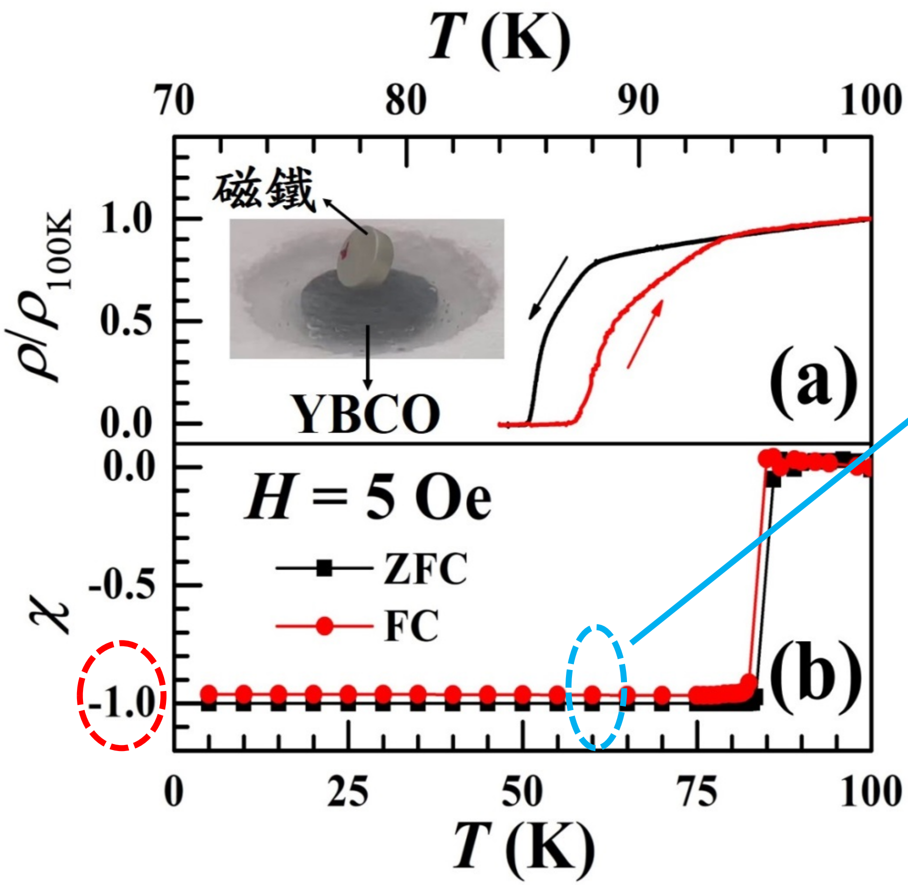


**Cu_2S exhibits a reduction in resistivity at around 385 K !

How to verify superconductors?

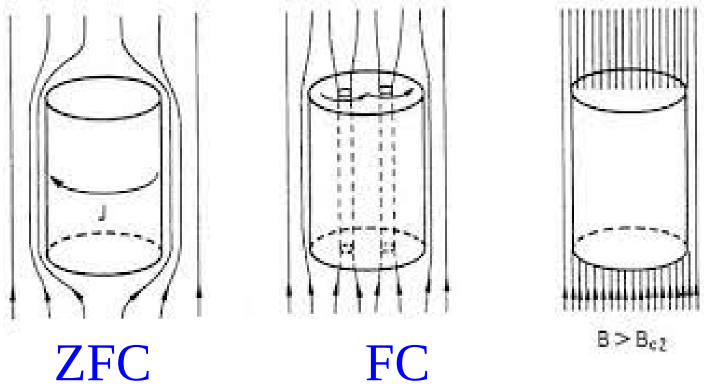
~Taking YBCO film as an example:



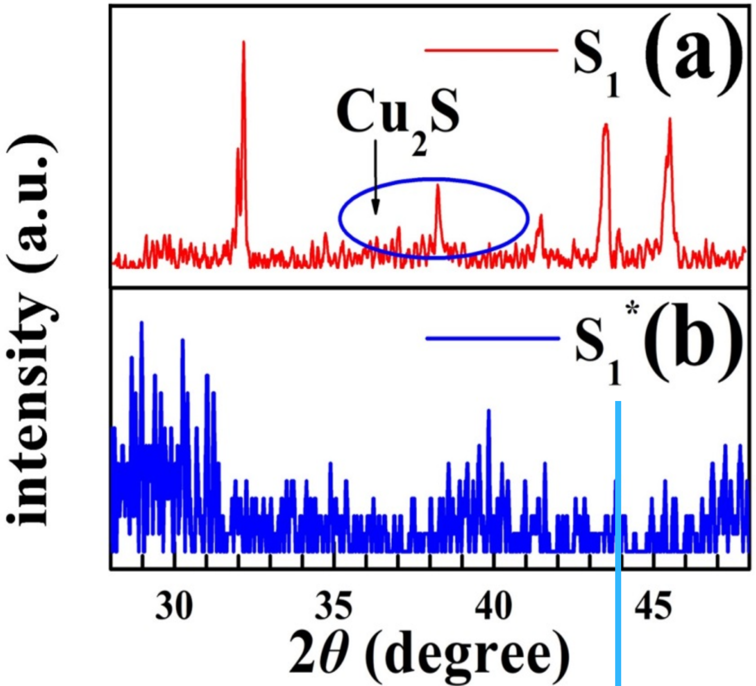


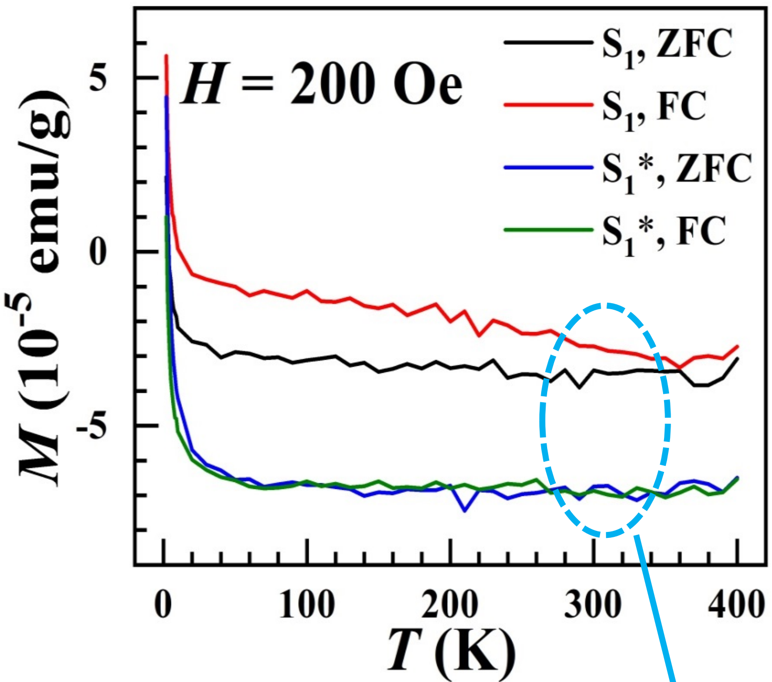
Type II SCs:

- ➢magnetic susceptibility $\chi = -1$ (perfect diamagnetism) @ zero-field cooling (ZFC)
- ➢@ field-cooling (FC), $\chi < 1$ (due to magnetic flux pinning)



Results: XRD & magnetization *M*–*T* measurements:

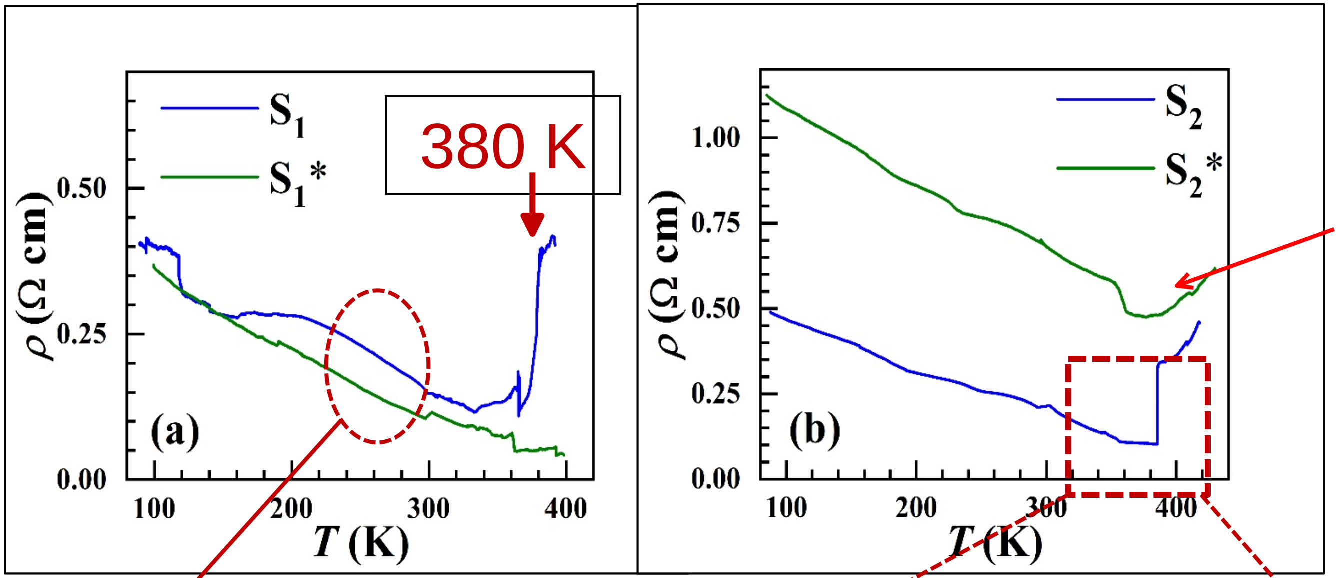




removal of Cu_2S using ammonia solution

diamagnetism(M <0)

Results~ electrical measurement (resistivity, temperature, *T*):



Sharp transition near 380 K disappears in S_2* resistive transition is due to Cu_2S!

Semiconductor properties: *T*

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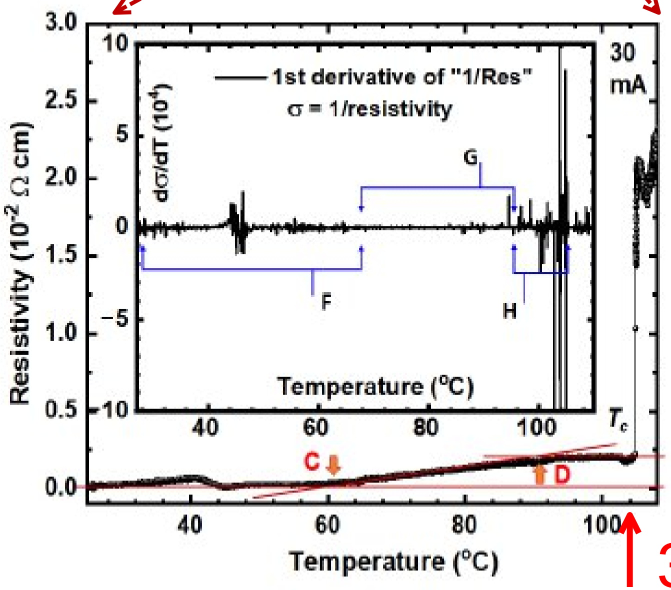
NEWS | 16 August 2023

LK-99 isn't a superconductor — how science sleuths solved the mystery

Efforts to replicate the material have pieced together the puzzle of why it displayed superconducting-like behaviours.

Dan Garisto

2023/08/16



378 K

Summary:

- A room-temperature ambient-pressure superconductor, LK-99, was announced by a Korean research team.
- We synthesized LK-99 and found that the Cu_2S phase can be effectively removed by ammonia solution.
- The superconducting-like behavior in LK-99 should originate from Cu_2S. LK-99 is considered as a diamagnetic semiconductor.
- Search for a room-temperature superconductor remains a challenge.

Thanks for your attention !