Correlated Oxides

Zenji HIROI
ISSP, Univ. of Tokyo

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東京大学
University of Tokyo

Institute for Solid State Physics
ISSP
Correlated Oxides

Zenji HIROI

Materials Design and Characterization Lab
Institute for Solid State Physics
University of Tokyo

Staff       Yoshihiko Okamoto, Jun-Ichi Yamaura
PD          Yui Ishii, (Goran Nilsen)
Students    Takashi Shimizu, Atsushi Onosaka
Millennium star (De Beers) 203 ct

Carbon atom

Diamond

Electron

Nucleus
Sodium crystal

“free” electron

Na atom

11th electron

Sodium
"Modern science is the search for new organizing principles of nature."
by R. B. Laughlin (1998 Novel prize) at Kashiwa, 2001
Strategy for new materials

Physics vs. Chemistry

“exact” analytical “about”

serious optimistic dreaming

the outcome limited

Some approximations necessary

often complicated and sometimes wired!

Active conversations are required.
Which topics or materials should we study?
Following the fashion, or going my way?
stimulated by a theoretical prediction?

From crystal structures to desired systems.
However, appearances are often deceptive.
Real materials always suffer from various obstacles.
<table>
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<th>Strategy for new materials</th>
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<tbody>
<tr>
<td>Physics vs. Chemistry</td>
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<td>Design vs. Serendipity</td>
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</table>

*Nature often complicated, but fascinating!*  
We should keep a humble attitude toward nature.  

- When I observe something predicted by theory, it’s OK but not so exciting.  
- When I observe something unexpected, I would be more happy.
Motivation of our research

New materials with novel properties

Transition metal oxides with strongly correlated electrons

Superconductivity, Magnetism, or Other exotic phenomena
High-Temperature Superconductors

銅酸化物超伝導体

$T_c = 135 \text{ K}$

(years)

- Hg1223(HP): Sep, 1993
- Hg1223: Apr, 1993
- Ti2223: Feb, 1988
- Bi2223: Jan, 1988
- Bi2212: Jan, 1988
- Y123: Jan, 1987
- (La,Sr)214: Apr, 1986
- (La,Ba)214: Apr, 1986

Temperature $T_c$ (K)

- Shuttle
- liq. H$_2$
- liq. N$_2$

Chemical Elements:
- Hg
- Pb
- Nb
- NbC
- NbN
- V$_3$Sn
- Nb$_3$Ge
- V$_3$Si
- Nb-Al-Ge

Timeline:
- 1900
- 1920
- 1940
- 1960
- 1980
- 2000

Geographic Points:
- Kyoto
- ISSP
- Year
Correlated Oxides:

I. A road to a room-temperature superconductor

II. Frustration and Cu minerals

III. Rattling good materials
Outline

- Introduction to superconductivity
- Copper oxide superconductors: Preparation and Materials
- Mechanism of the superconductivity
- Future prospect
Electrical Conductivity

Ohm's law

\[ V = R \times I \]
Electrical Conductivity

Ohm's law

\[ V = R \times I \]

“free” electrons in a metal \( \sim 10^{22} \) cm\(^{-3} \)

electron scattering \( \rightarrow \) resistivity
Discovery of superconductivity in 1911

by Kamerlingh Onnes

Nobel prize 1913

Hg: 水銀

Au: 金
BCS theory: Bardeen-Cooper-Schrieffer

Nobel prize in 1972

$T < T_c$

Two electrons form a pair $\rightarrow$ Cooper pair

$R \neq 0$

$R = 0$

not scattered!
What makes a Cooper pair?

Vibrations of ions (phonons) generate the attractive interaction.

\[ T_c \approx \text{vibration energy} \times 0.1 \approx 30 \text{ K} \]
Temperature

室温: 300 K

$T_c$ is too low!

“BCS wall”

$T_c < 30$ K

Liquid Nitrogen: 77 K

Helium: 4.2 K

-273°C
SC is helpful

Ohm’s law

\[ V = R \times I \]

Joule heating

If \( R = 0 \), no Joule heating, no energy loss!

\( R < 10^{-24} \Omega \)
Superconducting cables

- 100 times larger current
- Limited space in an underground public utility conduit
- Total energy loss less than half even with liq N$_2$ cooling
Global superconducting grid with natural energy generators

Solar-power generation in deserts
Wind-powder generation on seashores

proposed by Koichi Kitazawa
Strong magnets

- Superconducting magnets
- Electric power storage

$R < 10^{-24} \, \Omega$

Persistent current
Magnetic levitated train

Max speed: 581 km/h

levitated by 10 cm!
High-field applications

Ship motor

Consortium: 8 Entities

MRI

\[ B = 3,000 \sim 15,000 \text{ gauss} \]
Outline

- Introduction to superconductivity
- Copper oxide superconductors: Preparation and Materials
- Mechanism of the superconductivity
- Future prospect
The diagram shows the progression of superconducting materials and their critical temperatures ($T_c$) over time. The year 1911 marks the discovery of superconductivity in mercury (Hg). The "BCS wall" refers to the boundary beyond which superconductivity is observed, which is typically around liquid nitrogen temperatures ($\text{liq. } \text{N}_2$). Materials such as Pb, Nb, NbC, NbN, V$_3$Sn, Nb$_3$Ge, and others are highlighted, indicating their respective critical temperatures. The x-axis represents the year, starting from 1900 to 2010.
J. G. Bednortz & K. A. Müller

Physics Novel Prize in 1987

Summer in 1987 at the Bando lab. in Kyoto Univ.

J. G. Bednortz  K. A. Müller
Discovery of a copper oxide superconductor

Possible High $T_c$ Superconductivity in the Ba-La-Cu-O System

“At the extreme forefront of research in superconductivity is the empirical search for new materials”.

“At the extreme forefront of research in superconductivity is the empirical search for new materials.” [1]. Transition-metal alloy compounds of $A15$ (Nb$_5$Sn) and $B1$ (NbN) structure have so far shown the highest superconducting transition temperatures. Among many $A15$ compounds, careful optimization of Nb–Ge thin films near the stoichiometric composition of Nb$_5$Ge by Gavalev et al. and Testardi et al. a decade ago allowed them to reach the highest $T_c=23.3$ K reported until now [2, 3]. The heavy Fermion systems with low Fermi energy, newly discovered, are not expected to reach very high $T_c$ [4].

Only a small number of oxides is known to exhibit superconductivity. High-temperature superconductivity in the Li–Ti–O system with onsets as high as 13.7 K was reported by Johnston et al. [5]. Their x-ray analysis revealed the presence of three different crystallographic phases, one of them, with a spinel structure, showing the high $T_c$ [5]. Other oxides like perovskites exhibit superconductivity despite their small carrier concentrations, $n$. In Nb-doped SrTiO$_3$, with $n=2\times10^{20}$ cm$^{-3}$, the plasma edge is below the highest optical phonon, which is therefore unshielded [6]. This large electron-phonon coupling allows a $T_c$ of 0.7 K [7] with Cooper pairing. The occurrence of high electron-phonon coupling in another metallic oxide, also a perovskite, became evident with the discovery of superconductivity in the mixed-valent compound BaPb$_{1-x}$Bi$_x$O$_3$ by Siegenthaler et al., also a decade ago [8]. The highest $T_c$ in homogeneous oxygen deficient mixed crystals is 13 K with a comparatively low concentration of carries $n=2-4\times10^{21}$ cm$^{-3}$ [9]. Flat electronic bands and a strong breathing mode with a phonon feature near 100 cm$^{-1}$, whose intensity is proportional to $T_c$, exist [10]. This last example indicates that within the BCS mechanism, one may find still higher $T_c$’s in perovskite-type or related metallic oxides, if the electron-phonon interactions and the carrier densities at the Fermi level can be enhanced further. Strong electron-phonon interactions in oxides can occur owing to polaron formation as well as in mixed-valent systems. A superconductivity (metallic) to bipolaronic (insulator) transition phase diagram was proposed theoretically by Chakravarty [11]. A mechanism for polaron formation is the Jahn-Teller effect, as studied by Höch et al. [12]. Isolated Fe$^{2+}$, Ni$^{2+}$ and Cu$^{2+}$ in octahedral oxygen environment
USO

“Uso” means “lie” in Japanese.

UFO = Unidentified Flying Object
USO = Unidentified Superconducting Object

$T_c = 330$ K!? 

PbCO$_3 \cdot 2$PbO + Ag$_2$O and PbCO$_3$ · PbO + Ag$_2$O (PACO) systems: route for novel superconductors

D. Djurek $^{a,*}$, Z. Medunić $^a$, A. Tonejc $^b$, M. Paljević $^c$

$^a$ A. Volta Applied Ceramics (AVAC), Fundamental and Applied Research, Kasten bribery 5, HR-10000 Zagreb, Croatia
$^b$ Department of Physics, Faculty of Sciences, Bijenička 32, HR-10000 Zagreb, Croatia
$^c$ Ružer Bošković Institute, Bijenička 54, HR-10000 Zagreb, Croatia
$\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$

$\text{Cu}^{2+} \rightarrow \text{Cu}^{2+p}$ (hope doping), as $\text{La}^{3+}$ is replaced by $\text{Sr}^{2+}$.

$T_c = 40 \text{ K}$ by H. Takagi
Cooper pairs are formed in the CuO$_2$ plane, when holes are introduced.
Figure showing the increase in critical temperature ($T_c$) over time, with various materials such as Hg, Pb, Nb, NbC, NbN, V$_3$Sn, Nb$_3$Ge, V$_3$Si, Nb-Al-Ge, (La,Sr)$_{214}$, and (La,Ba)$_{214}$, reaching a peak in 1986 at Kyoto.
### Superconducting race

#### Periodic Table

<table>
<thead>
<tr>
<th>IA</th>
<th>IIA</th>
<th>IIIA</th>
<th>IVA</th>
<th>VA</th>
<th>VIA</th>
<th>VIIA</th>
<th>VIII</th>
<th>IB</th>
<th>IIB</th>
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<td>Au</td>
<td>Hg</td>
<td>Tl</td>
<td>Pb</td>
<td>Bi</td>
</tr>
</tbody>
</table>

#### Notes:
- La-Ba-Cu-O
- La-Sr-Cu-O

Let’s replace La by other Rare earth.

*try to catch lightning in a bottle twice*

= *try to catch weather fish twice under willow (in Japanese)*
How to make HTSCs

starting materials

目的の混合比となるように秤量する

よく混ぜる

電気炉で加熱し反応させる（焼成）

粉末を固める

超伝導体の出来上がり

必要に応じてアンネル（焼鈍）

もう一度加熱（焼成）

superconductors!
Phase Diagram: map for complex compounds

**Y-Ba-Cu-O system**

950°C in air

Y-Ba-Cu-O


**La-Sr-Cu-O system**

950°C in O₂

La₂-xSrₓCuO₄

Y$_2$O$_3$-BaO-CuO system

950°C in air

"Y$_{2-x}$Ba$_x$CuO$_4$"

New SC YBa$_2$Cu$_3$O$_7$

$T_c = 90$ K!

S.J. Hwe et al., J. Am. Ceram. Soc. 70, C165 (1987)
Professor Koichi Kitazawa

‘Superconductivity Course’
by Shoutaro Ishinomori
Kodansha, 1988

8,400 yen @amazon.com
$T_c$ Jumps up above 77 K!

- Shuttle
- liq. $\text{N}_2$
- liq. $\text{H}_2$
- $\text{Hg}$
- $\text{Pb}$
- $\text{Nb}$
- $\text{NbC}$
- $\text{NbN}$
- $\text{V}_3\text{Sn}$
- $\text{Nb}_3\text{Ge}$
- $\text{V}_3\text{Si}$
- $\text{Nb-Al-Ge}$
- $\text{(La, Sr)214}$
- $\text{(La, Ba)214}$

Year:
- 1900
- 1920
- 1940
- 1960
- 1980
- 1990
- 2000
- 2010

$T_c$ (K)
La$_2$CuO$_4$ \((La,Sr)_{2}CuO_4\)

$T_c = 40$ K

Removable Oxygen

$T_c = 90$ K

CuO$_x$ chan

La/ Sr

YBC/Y123

YBa$_2$Cu$_3$O$_{7-\delta}$

$T_c = 90$ K

CuO$_2$面

90 K Superconductor
Interesting crystal chemistry in $\text{YBa}_2\text{Cu}_3\text{O}_{7-d}$

$0 \leq \delta \leq 1$


Hiroshi Maeda

Resistance (Arbitrary Scale)

Temperature (K)

1988

National Lab. at Tsukuba
90 K Superconductors

\( T_c = 90 \text{ K} \)

CuO\(_x\) chain

Y

Ba

YBa\(_2\)Cu\(_3\)O\(_{7-\delta}\)

YBC/Y123

T\(_c\) = 90 K

Bi

Sr

Ca

Bi\(_{2}\)Sr\(_2\)CaCu\(_2\)O\(_8\)“
$T_c = 90 \text{ K}$

$T_c = 110 \text{ K}$

CuO$_x$ chain

CuO$_2$ planes

YBC/Y123

YBa$_2$Cu$_3$O$_{7-\delta}$

Bi

Sr

Ca

“Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10}$”
Phase diagram in the Bi-Sr-Ca-Cu-O system

Bi2212

Bi2223

Hg1223
HgBa$_2$Ca$_2$Cu$_3$O$_{8+\delta}$

World record $T_c$:
135 K @ AP
160 K @ HP

with a beautiful crystal structure
Electron Microscopy
$\text{HgBa}_2\text{Ca}_3\text{Cu}_4\text{O}_{10+x}$
HTSC: plate crystals

Hiroi, Shohei

crystal  plate
Outline

- Introduction to superconductivity
- Copper oxide superconductors: Preparation and Materials
- Mechanism of the superconductivity
- What determines the $T_c$?
- Future prospect
Mean-field or one-electron approximation assumes uniform potential $V$ from other electrons.

Free electrons + periodic potential from ions = Bloch electrons

$\begin{align*}
\text{t: kinetic energy} \\
\text{t} \propto W: \text{bandwidth}
\end{align*}$

However, electrons are not completely free, but there is always Coulomb repulsion between them.

$\begin{align*}
\text{U: Coulomb repulsion or electron correlation}
\end{align*}$
Strongly correlated electron system: SCES

Electron correlation $U$ vs. Bandwidth $W$

- **Itinerant**
  - ion
  - electron
  - charge

- **Localized**
  - Antiferromagnetic
  - spin

- **Metal**
  - $s$ electrons
  - Large $W$

- **SCES**
  - $d$ electrons
  - Small $W$
  - Large $U$

- **Insulator**
  - Large $U$
Strongly correlated electron systems

delocalized

- \( t \)

hole doping

Mott insulators

localized

+ \( U \)

on-site correlation: \( U \)

correlated metals
What determines the $T_c$?

Superconductivity = electron pairs (Cooper pairs)

\[ T_c = \omega \exp \left( -\frac{1}{\lambda} \right) \]

An excitation to generate pairing "glue"

Phonon: $\omega = \omega_{ph} \sim 300$ K  $$\Rightarrow T_c \sim 300 \times 0.1 = 30$ K

"BCS wall"

What is the glue for copper oxides?
Copper oxides

\[ d_{x^2-y^2} \quad \text{Cu}^{2+}: 3d^9 \]

\[ d_{3z^2-r^2} \quad \text{One electron/hole in the nondegenerate orbital} \]

very rare!

corner-sharing chain

\[ J: \text{antiferromagnetic coupling} \]

\[ J = 2,200 \text{ K} \]

\[ J = 1,500 \text{ K} \]

Cu\(^{2+}\)O\(_4\) square with an \( S = 1/2 \) spin is a motif to build up various types of low-dimensional structures!
Hole doping and HTSC in the CuO$_2$ plane

$E = -4J - 4J = -8J \rightarrow -7J$

hole pairs on oxygens in a spin liquid made of Cu spins

hole doping

Zhang-Rice singlet

strongly correlated electron system

a pair of Z-R singlets, Cooper pair

Superconductivity
Mechanisms of the superconductivity

**phonons** in any lattice

$k$-space pairing

\[ T_c \propto \omega_{\text{ph}} \sim \omega_D \sim 300 \text{ K} \]

**spins** in the CuO$_2$ plane

real-space pairing?

\[ T_c \propto \langle J \rangle : J \sim 1,500 \text{ K} \]
What determines the $T_c$?

$T_c \propto$ Binding energy of Cooper pairs

$T_c = \omega \exp \left( -\frac{1}{\lambda} \right)$

Energy of relevant excitations

Damping factor

Phonon: $\omega = \omega_{ph}$

$T_c \sim 400 \times 0.1 = 40$ K

Antiferromagnetic interaction: $\omega = J$

$T_c \sim 1,500 \times 0.1 = 150$ K
Questions

What is a materials factor that decides the $T_c$?

Any way to get over the record?
What determines the $T_c$?

$T_c \propto \text{Binding energy of Cooper pairs}$

$$T_c = \omega \exp\left(-\frac{1}{\lambda}\right)$$

Energy of relevant excitations \underline{Damping factor}

Phonon: $\omega = \omega_{\text{ph}}$ \hspace{1cm} $T_c \sim 400 \times 0.1 = 40 \text{ K}$

Antiferromagnetic interaction: $\omega = J$ \hspace{1cm} $T_c \sim 1,500 \times 0.1 = 150 \text{ K}$

What is the damping factor for the copper oxides?

If doubled, $T_c$ becomes room temperature!
What determines the $T_c$?

Hole density

$T_c$ forms a dome with a maximum.

La$_{2-x}$Sr$_x$CuO$_4$

Cu$^{2+p}$O$^{2-}$

$\{(La^{3+},Sr^{2+})O^{2-}\}_2$
$T_c$ vs. number of CuO$_2$ planes

Always $T_c$ reaches a maximum at three layers!
What determines the maximum $T_c$?

1. **Apical oxygens**, instead of number of CuO$_2$ planes

2. **Randomness** induced by chemical substitutions
$T_c$ dome: role of the apical oxygens

As the apical oxygen approaches to the CuO$_2$ plane, holes move from in-plane oxygen p orbital to Cu d orbital.

ZR singlets collapse to be just d holes.

CuO$_2$ plane without apical oxygens is ideal.
$T_c$ dome: role of apical oxygens

A pair of Zhang-Rice singlets is superconducting.

Effect of apical O

Collapse of the background AF spin sea

$T_B$: Bose condensation $T$ for ZR singlets $\propto (p'/2)$

$T_s$: Binding energy from AF fluctuations

$d$ holes

normal metal
$T_c$ vs. number of CuO$_2$ planes

- **1** single plane
  - CuO$_2$ plane
  - apical O

- **2** double planes

- **3** triple planes

CuO$_2$ plane without apical oxygen
Further increasing the number of CuO$_2$ planes

Hole density

The middle plane can be doped optimally.

substituted metals or excess oxygens

Total number of holes there is limited.

Hole density is not enough for more planes.

Number of CuO$_2$ sheets versus $T_c$

- Hole density is not enough for more planes.

- The middle plane can be doped optimally.

- Total number of holes there is limited.
What determines the maximum $T_c$?

1. **Apical oxygens**, instead of the number of CuO$_2$ planes

2. **Randomness** induced by chemical substitutions or excess oxygens
F = E - TS

E = N\int{xV_{AA} + (1-x)V_{BB} + 2x(1-x)V}/2: V = V_{AB} - (V_{AA} + V_{BB})/2

-TS = Nk_B T\{x\ln x + (1-x)\ln(1-x)\}

\begin{align*}
V < 0 & \quad \text{Solid solution} \\
V > 0 & \quad \text{Phase separation}
\end{align*}
Random distribution of impurities

5% impurities on 20x20 lattice

superconducting coherence length $\xi \sim 3$ nm

impurity ion
“Uniform” Solid Solutions

9 impurity ions on the 10x10 lattice

always results in an inhomogeneous distribution of impurities!
Effects of randomness

Some holes are trapped by the randomness and cannot move.

1. Substituted metals or excess oxygens
2. Charge reservoir
3. "Clean" CuO₂ sheet

- Single sheet
- CuO₂ sheet
- Double sheets
- Triple sheets

- Pair density $p/2$

- $T_B$: BEC temperature $\propto p^{2/3}$: 3D
- $p$: 2D

- Weak localization
- Spin glass
$T_c$ vs. number of CuO$_2$ planes

Always $T_c$ reaches a maximum at three layers!
How to raise $T_c$?

$Hg1223$ is almost perfect!

$T_c \approx J \times 0.1$

Less effect of apical oxygens

$T_c^{max} = 135 \text{ K}$

$T_c \approx 160 \text{ K at HP}$
When holes are introduced into a single CuO$_2$ plane without any disturbance, ...
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What determines the $T_c$?

Superconductivity = electron pairs (Cooper pairs)

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An excitation to generate pairing "glue"

Phonon: $\omega = \omega_{ph} \sim 300$ K

$T_c \sim 300 \times 0.1 = 30$ K

"BCS wall"

Antiferromagnetic interaction: $\omega = J \sim 1500$ K

$T_c \sim 1,500 \times 0.1 = 150$ K

More glues available for SC?
Let’s find another lattice to be doped with carriers!
High-resolution electron microscopy

Hiroi & Horiuchi
Ladder compounds

two-leg ladder

SrCu$_2$O$_3$

three-leg ladder

Sr$_2$Cu$_3$O$_5$

between 1D and 2D
Superconductivity in the two-leg ladder

J ~ 2,000 K!

hole doping

pairing

theoretical prediction by E. Dagotto

SC found in (Ca,Sr)$_{14}$Cu$_{24}$O$_{41}$

Ca$_{11.5}$Sr$_{2.5}$Cu$_{24}$O$_{41}$
Single crystal
Uehara et al.

1996

Resistivity (mΩcm)

3.0 GPa
3.5 GPa
4.0 GPa
6.0 GPa

Temperature (K)
Squares to triangles

More interesting Superconductors?

α-pyrochlore \( \text{Cd}_2\text{Re}_2\text{O}_7 \)

β-pyrochlore \( \text{AOs}_2\text{O}_6 \)

\( \text{Na}_x\text{CoO}_2 \cdot y\text{H}_2\text{O} \) (Takada)

CuO\(_2\) plane

pyrochlore lattice
1. **Increase $\omega$!**

<table>
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<tr>
<th>Fundamental interaction</th>
<th>Energy scale</th>
<th>Maximum $T_c$</th>
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<tbody>
<tr>
<td>phonons</td>
<td>$\omega \lesssim 300$ K</td>
<td>30 K</td>
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<tr>
<td>spins</td>
<td>$\omega = J$</td>
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<tr>
<td>2D AF</td>
<td>$J \sim 1500$ K</td>
<td>150 K</td>
</tr>
<tr>
<td>1D AF</td>
<td>$J \lesssim 3000$ K</td>
<td>$\times$</td>
</tr>
<tr>
<td>FM</td>
<td>$J_{FM} \ll J_{AF}$</td>
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Exitons (1D or interface)
Charge fluctuations, ...

2. **Increase $V$!**

but, $V \uparrow$; $\omega \downarrow$ in phonons.

3. **Suppress competing order!**

$T_c \rightarrow \omega$, as $VN(E_F) \uparrow$

Dimensionality: 3D $>$ 2D $< 1$D
Frustration
Carrier doping
Superconductivity

Prospecting for an iron age

Paul M. Grant

Different material options for high-temperature superconductivity — conduction of electricity with little or no resistance at 'practical' temperatures — have arrived. Iron compounds are the latest thing.

\[ T_c = 54 \text{ K} \]

Bronze Age

Iron Age

Hg-1223

2008

HgFeAsO

SmFeAsO

BaFe\text{\textsubscript{2}}As\text{\textsubscript{2}}

LaFeAsO

CaFe\text{\textsubscript{2}}As\text{\textsubscript{2}}
Superconductivity in FeTe$_{1-x}$S$_x$ induced by alcohol

Keita Deguchi$^{1,2,3}$, Yoshikazu Mizuguchi$^{1,2,3}$, Toshinori Ozaki$^{1,3}$, Shunsuke Tsuda$^{1,3}$, Takahide Yamaguchi$^{1,3}$ and Yoshihiko Takano$^{1,2,3}$

1. National Institute for Materials Science, 1-2-1
2. University of Tsukuba, 1-1-1 Tennodai, Tsukuba
3. JST TRIP, 1-2-1, Sengen, Tsukuba, 305 0047,

may be suitable for Nature or Science, but not for Journals!
If there is a room-temperature superconductor, unnecessary for cooling, already $\rho = 0$ in a chilly morning, and have to warm it to measure the transition.

Is it good for applications?

New materials science?

Interesting physics behind?

Nobel prize?
Where is a room-temperature superconductor?

Those who have been working on the copper oxides for many years may not be able to find it.

For young people, just forget my story and try!
What would happen when it is doped with carriers?
図 9.10 擬 2 次元ないし 3 次元ハバード・モデルの相図
超伝導ペアリングの可能性は未だ考慮されていない。T 軸に垂直な面内の
陰影部分は T 軸に沿って上に伸ばした空間領域を意味する。
クーパー対形成によるBCS超伝導

分子ボゾンのボーズーアインシュットイン凝縮

BCS-BEC Crossover

高温超伝導との類似性

強结合
反強磁性バックグラウンドによる
強い引力
フォノンなどの「のり」はない
小さなクーパーペア

Tc以上でクーパーペアは出来るが波動関数は重ならない
TcでBEC, つまり, 超伝導
Tcは密度に比例 (2D)

弱結合
引力低下と共にTcは下がる
大きなクーパーペア
Tcでペアが出来ると同時に
波動関数は重なる
クーパー対形成と超伝導
転移は同時に起こる
弱結合BCS領域
Tcは相互作用の大きさによる

$k_B T_c = (2\pi \hbar^2 / m) (n/2.612)^{2/3}$

$n \cdot \lambda_{\text{th}}^3 = 2.612$

クーパー対形成にフェルミ面は不要！
Basic idea of the BCS-type superconductivity

\[ 2\Delta = 3.5k_B T_c \]

\[ T_c = \omega_{ph} \exp \left( -\frac{1}{VN(E_F)} \right) \]
PROPOSED MAGLEV PATHS

K. Kitazawa: Moscow Int. Conf. MSU 2001
Uemura plot & Maekawa plot

$T_c$ vs $n_s/m^*$

![Graph showing $T_c$ vs $n_s/m^*$ with data points and curves.]

$T_c$ vs $\Delta V_A$

![Graph showing $T_c$ vs $\Delta V_A$ with data points and shaded region.]

$\Delta V_A = V_{O(A)} - V_{O(P)}$


Multilayered Superconductors

Hg1245 with 5 CuO$_2$ planes

$T_c = 108$ K

AF with less holes

$T_c = 108$ K

Bi HTSCs

Large single crystals