RTS Workshop Theory Summary

June 22, 2007
Loen, Norway

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Theory of Superconductivity*

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(Received July 8, 1957)

A theory of superconductivity is presented, based on the fact that the interaction between electrons resulting from virtual exchange of phonons is attractive when the energy difference between the electrons states involved is less than the phonon energy, $\hbar\omega$. It is favorable to form a superconducting phase when this attractive interaction dominates the repulsive screened Coulomb interaction. The normal phase is described by the Bloch individual-particle model. The ground state of a superconductor, formed from a linear combination of normal state configurations in which electrons are virtually excited in pairs of opposite spin and momentum, is lower in energy than the normal state by amount proportional to an average $(\hbar\omega)^2$, consistent with the isotope effect. A mutually orthogonal set of excited states in one-to-one correspondence with those of the normal phase is obtained by specifying occupation of certain Bloch states and by using the rest to form a linear combination of virtual pair configurations. The theory yields a second-order phase transition and a Meissner effect in the form suggested by Pippard. Calculated values of specific heats and penetration depths and their temperature variation are in good agreement with experiment. There is an energy gap for individual-particle excitations which decreases from about $3.5kT_c$ at $T=0°\text{K}$ to zero at T_c. Tables of matrix elements of single-particle operators between the excited-state superconducting wave functions, useful for perturbation expansions and calculations of transition probabilities, are given.

.B. Pippard-- Concluding remarks Colgate Conference on Superconductivity 1963

“The dominant impression has been the overwhelming success of the BCS theory not only in explaining what was known about superconductivity but in providing a framework for new developments.”

.B. Pippard-- Concluding remarks Colgate Conference or Superconductivity 1963

However I would ask several questions:

1. Are phonon interactions the only interactions that can cause superconductivity?

2. How high can Tc go?

Impact in Condensed Matter

The BCS theory provided an explanation of the superconductivity of a wide variety of materials.

“s-wave” electron-phonon superconductors

~ 50 elements $Hg \quad Pb \quad Nb \quad S \quad Ca \quad Li$

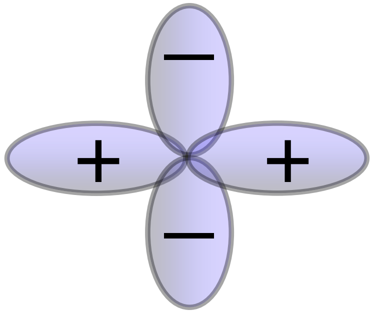
thousands of compounds $Nb_3Ge \quad MgB_2$

fullerenes Cs_3C_{60}

graphite intercalation compounds CaC_6

It also provides a framework for understanding the superconducting state of non s-wave, non-phonon-mediated superconducting or superfluid systems.

heavy fermion $CePt_3Si$ $PuCoGa_5$



~50 cuprates $YBa_2Cu_3O_{7-x}$

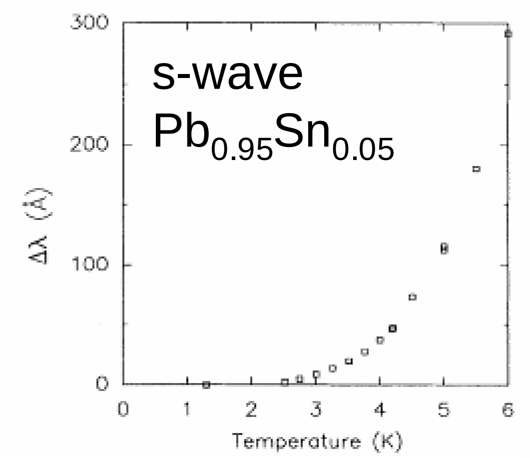
d-wave

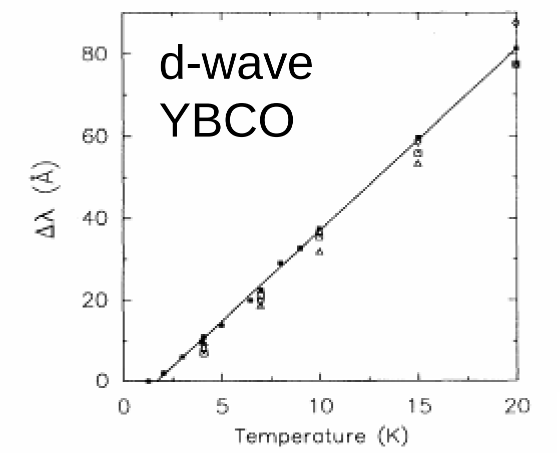
ruthenates Sr_2RuO_4 $(p_x + ip_y)$-wave

Superfluid He^3 (p-wave)

$d_{x^2-y^2}$ symmetry of superconducting gap

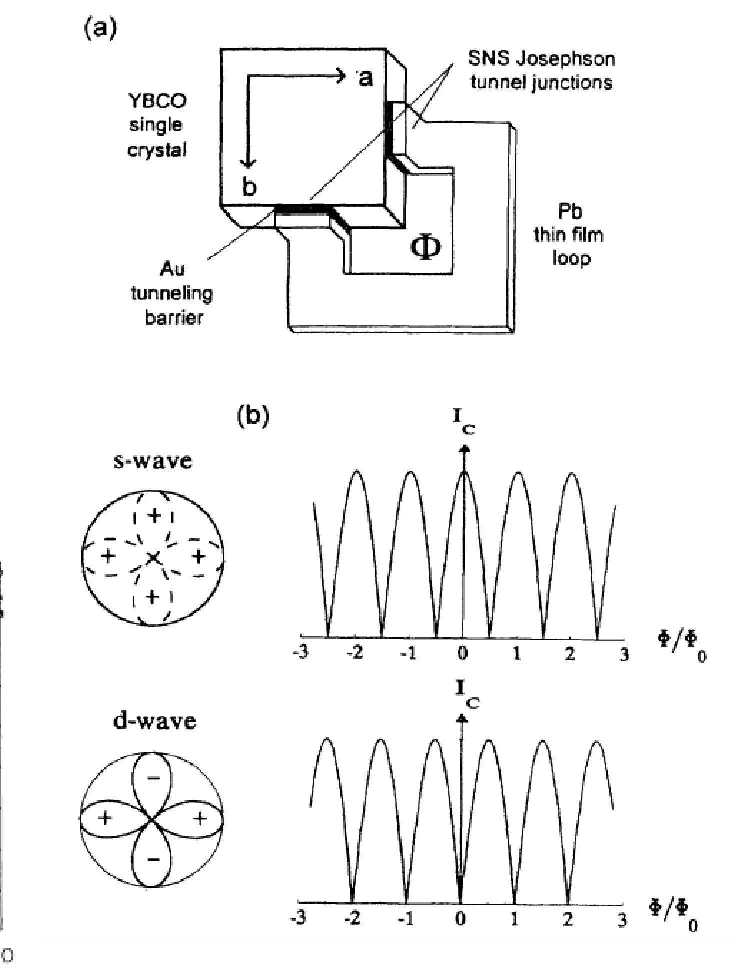
Penetration depth
(by microwave cavity)





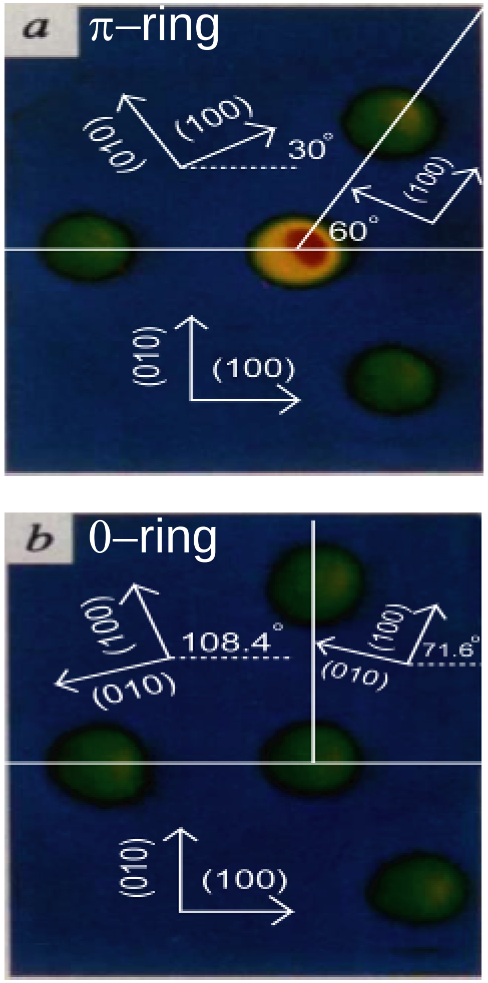
W. N. Hardy *et al*. Phys. Rev. Lett. **70** 3999 (1993).

dc-SQUID

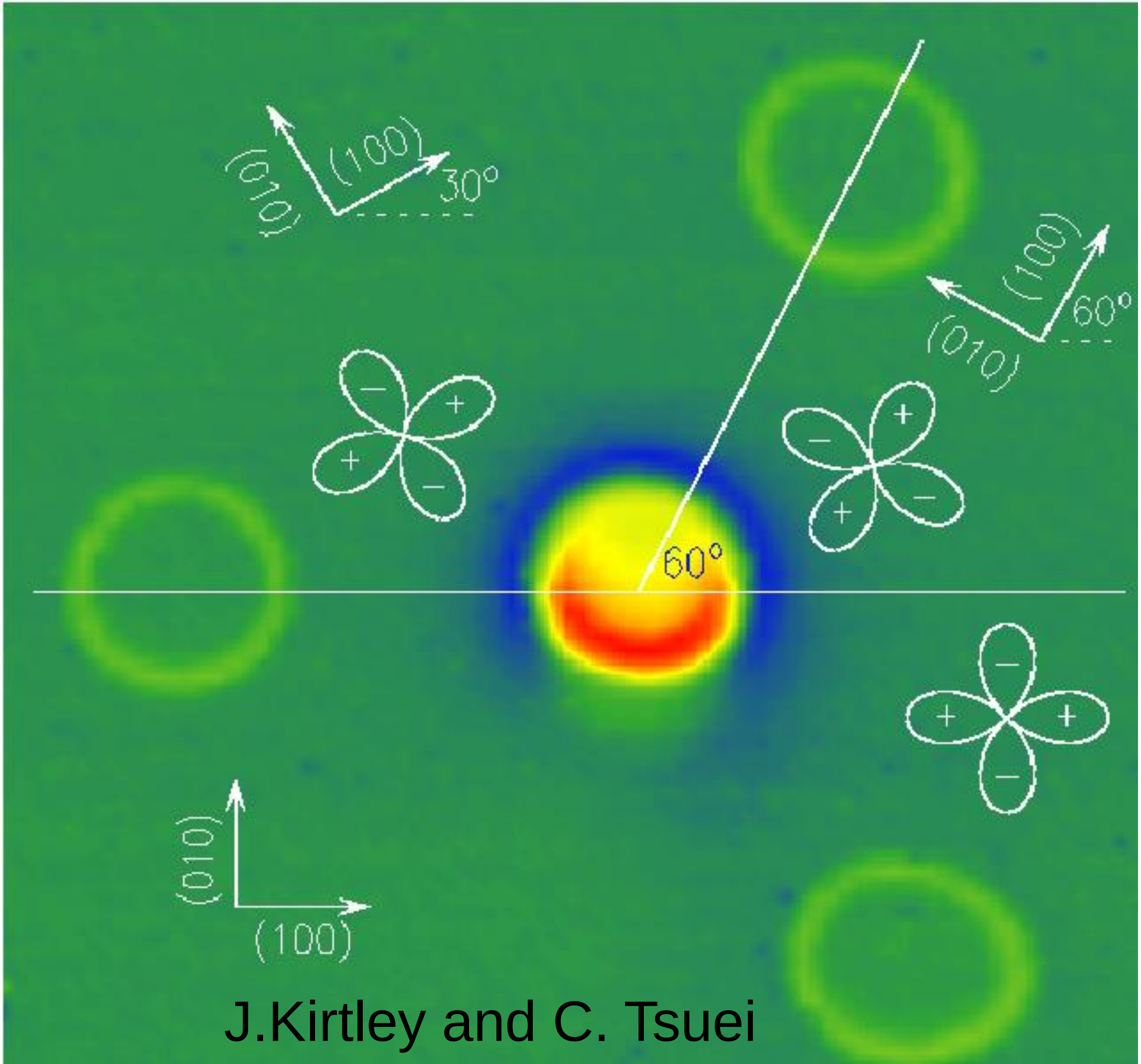


D. A. Wollman *et al*. Phys. Rev. Lett. **71** 2134 (1993).

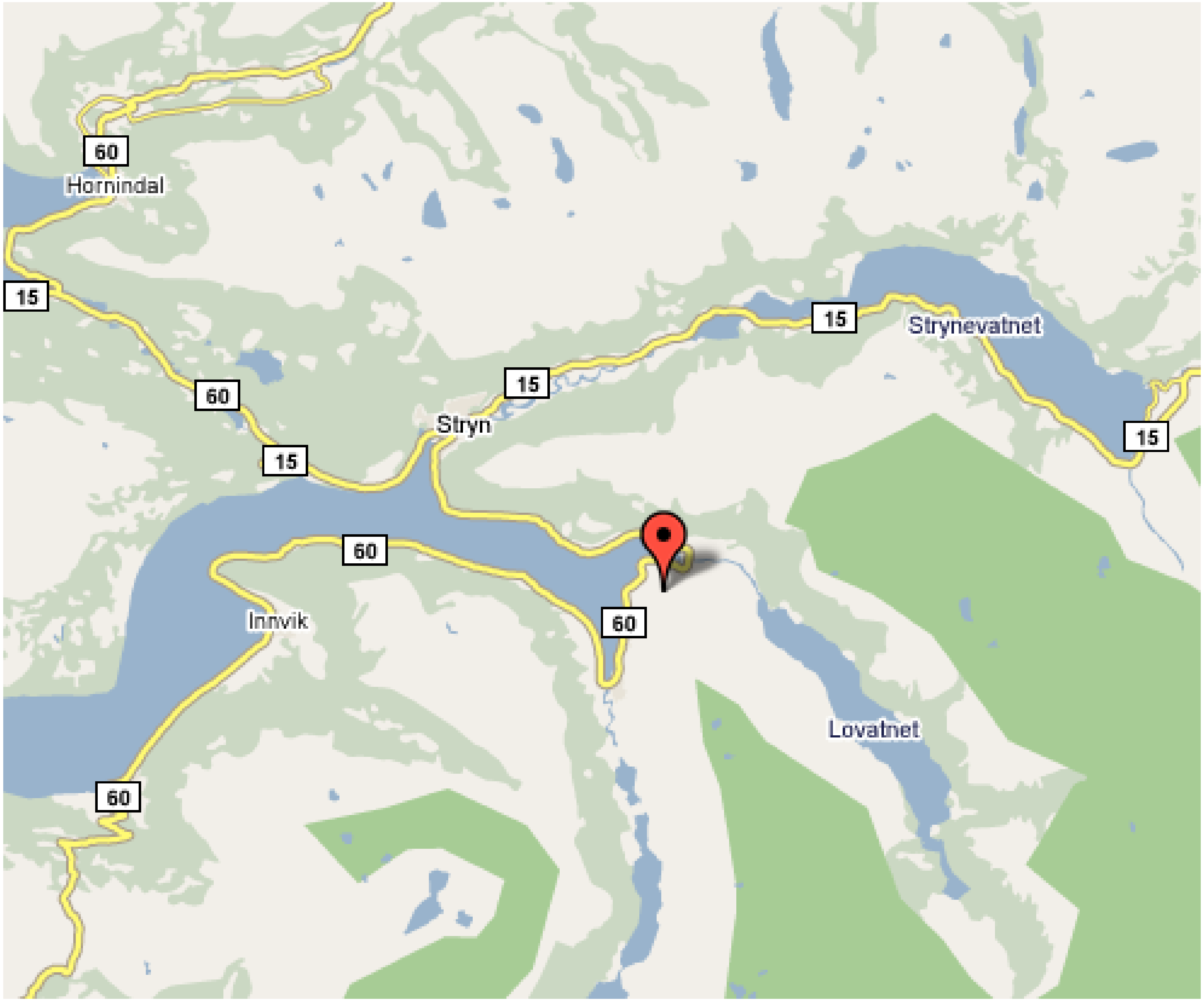
Scanning SQUID Spectroscopy



J. R. Kirtley *et al*. Nature **373**, 225 (1995).



J.Kirtley and C. Tsuei


60
Hornindal
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Little-Ginzburg Road


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Little-Ginzburg Road

Eliashberg Gate

RTS

Microstructures Avenue

Negative U Way

Strongly Correlated Strasse

Little-Ginzburg Road

Eliashberg Gate

RTS

Another Gate

Microstructures Avenue

Negative U Way

Strongly Correlated Strasse

1. Eliashberg Gate

$$T_c = 0.18\sqrt{\lambda < \omega^2 >} \approx \sqrt{\frac{\eta^2}{M}}$$

A stronger electron-phonon coupling η and lighter ions.

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A stronger electron-phonon coupling η
and lighter ions.

MgB_2

C_{60}

C_{36}

boron doped diamond

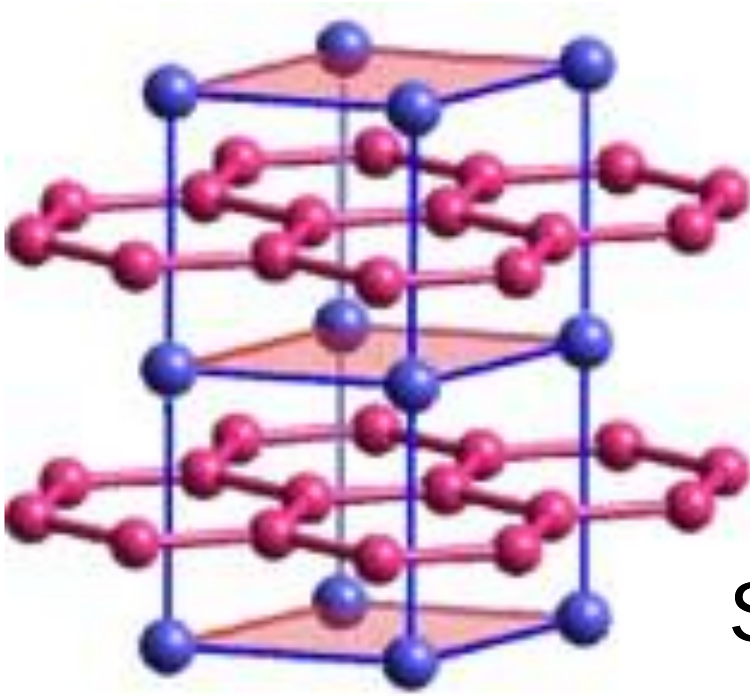
1. Eliashberg Gate

$$T_c = 0.18\sqrt{\lambda < \omega^2 >} \approx \sqrt{\frac{\eta^2}{M}}$$

A stronger electron-phonon coupling η
and lighter ions.

Pressure H

Chemistry SiH_4 $Li(NH_3)_4$

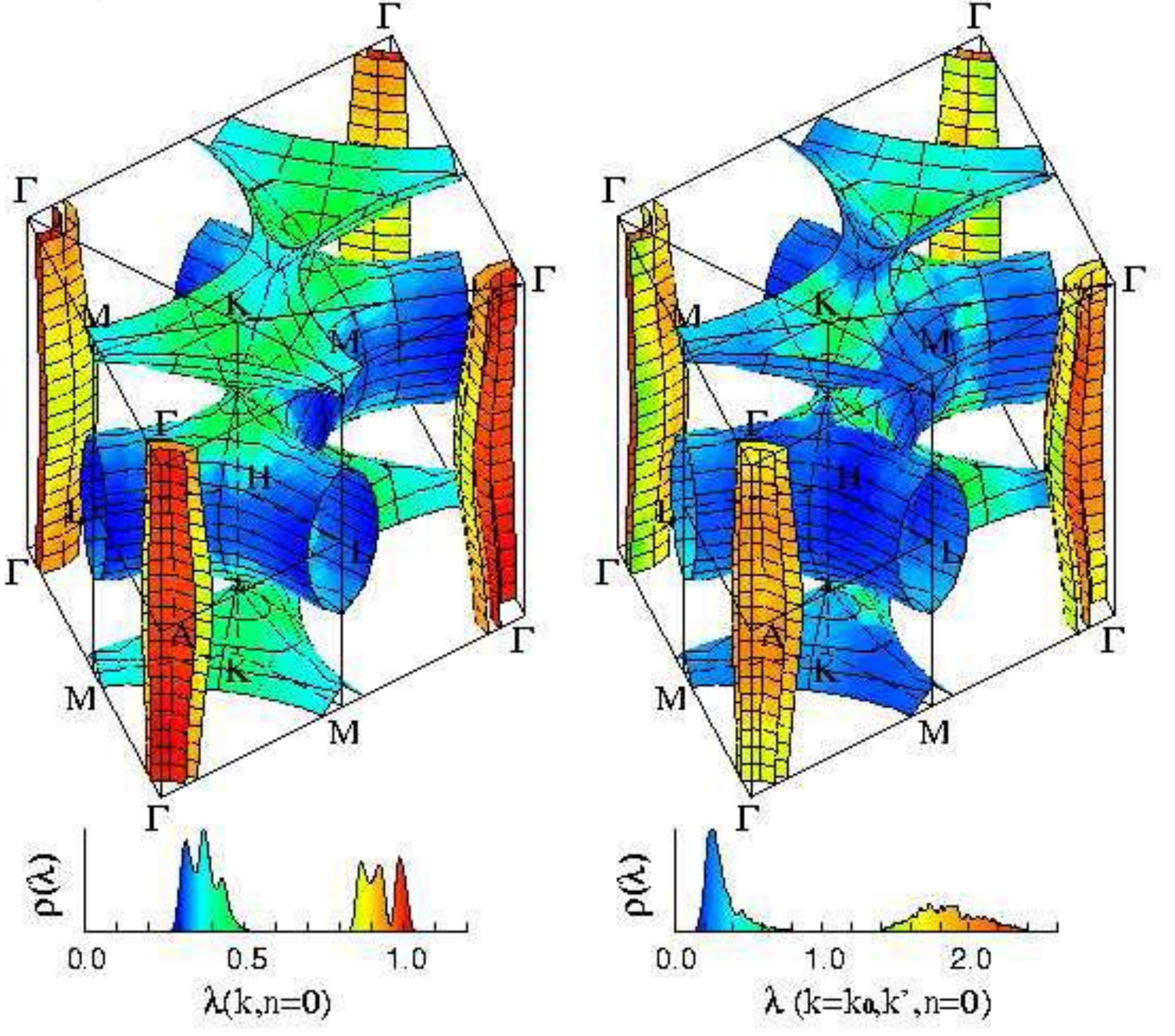


Mg-ions stabilize the lattice

B

Strong electron-phonon coupling mediated by “short covalent” B-B bonds.

MgB2


Γ
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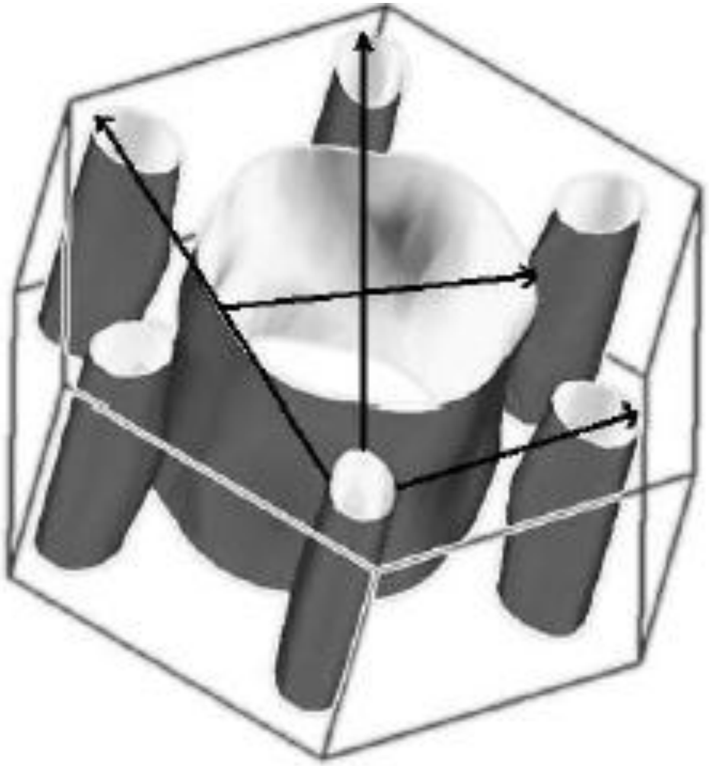
Γ
M
K
M
Γ
H
L
L
Γ
A
K
M
M
Γ
Γ
ρ(λ)
0.0
0.5
1.0
λ(k,n=0)
ρ(λ)
0.0
1.0
2.0
λ (k=k0,k',n=0)

Pickett’s suggestion



Questions

Need to suggest possible crystal structures to implement the formation of fermi surfaces which can make use of more of the different phonons modes, but can remain stable.

Treat the core electrons and understand $\mu*$.

Limits of Eliashberg Theory and how Tc depends upon λ and Ω_0/E_F .

M. Cohen: real space structure of the pairing interaction

N. Ashcroft: additional local field extension of Kukkonen-Overhauser to treat the core electrons and $\mu*$

In a picture in which the spin-fluctuations provide the pairing interaction

$$V(q,\omega) \sim (3/2)\, \chi(q,w)$$

one can have a large $\frac{2\Delta_0}{kT_c}$ ratio because weight in $\chi''(q,\omega)$

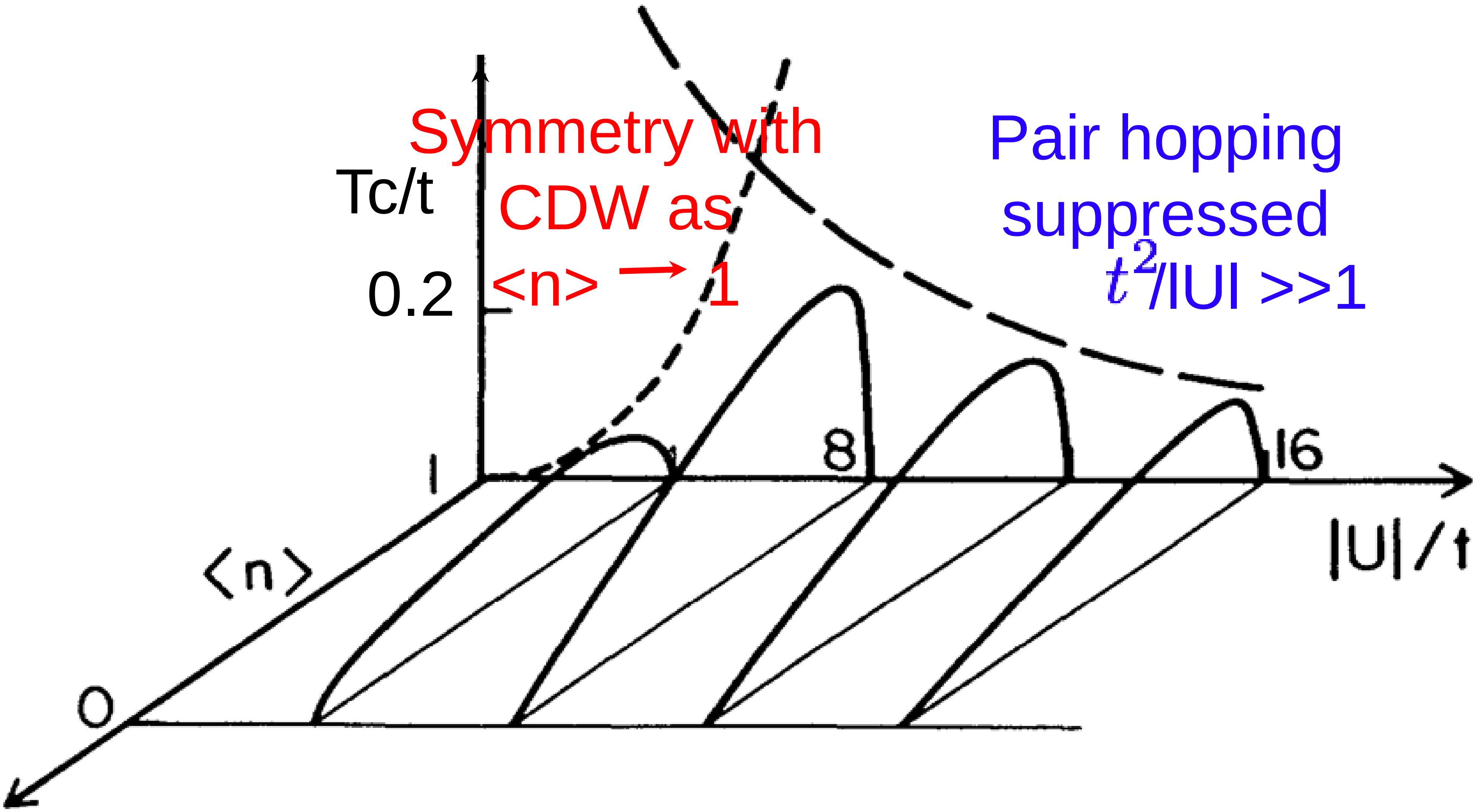
is shifted to higher frequencies when the system becomes superconducting

2. Negative U Way

$Ba_{1-x}K_xBiO_3$

Tl doped $PbTe$

O vacancies



Symmetry with CDW as <n> $\rightarrow$ 1

Pair hopping suppressed t^2/|U| >>1

Too large a value of $|U|$ suppresses Tc.

Doped away from half-filling the maximum

$$Tc \sim 0.2t$$

for the 2-D case is obtained for $|U| \sim 8t$ (the bandwidth).

For Tc=300K one needs

$$t \sim 5Tc = 125\text{meV}$$

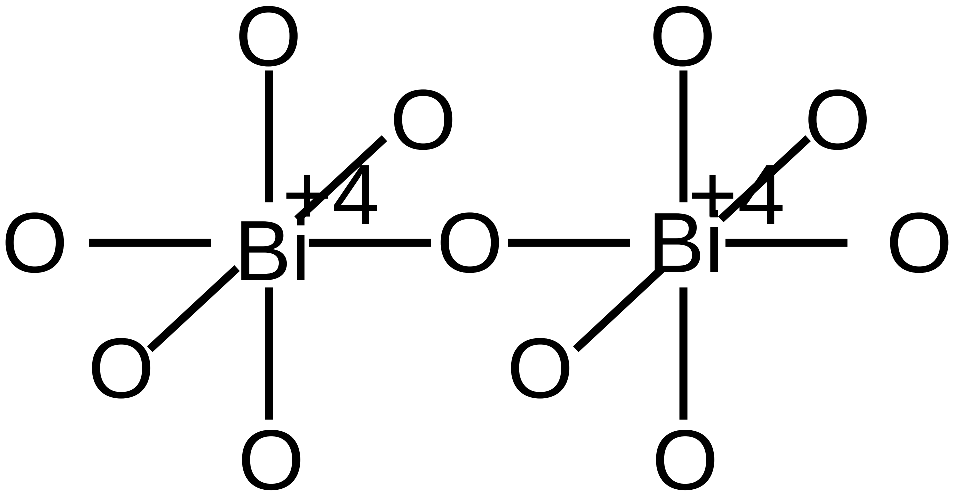
$$|U| \sim W = 8t = 1\text{eV}$$

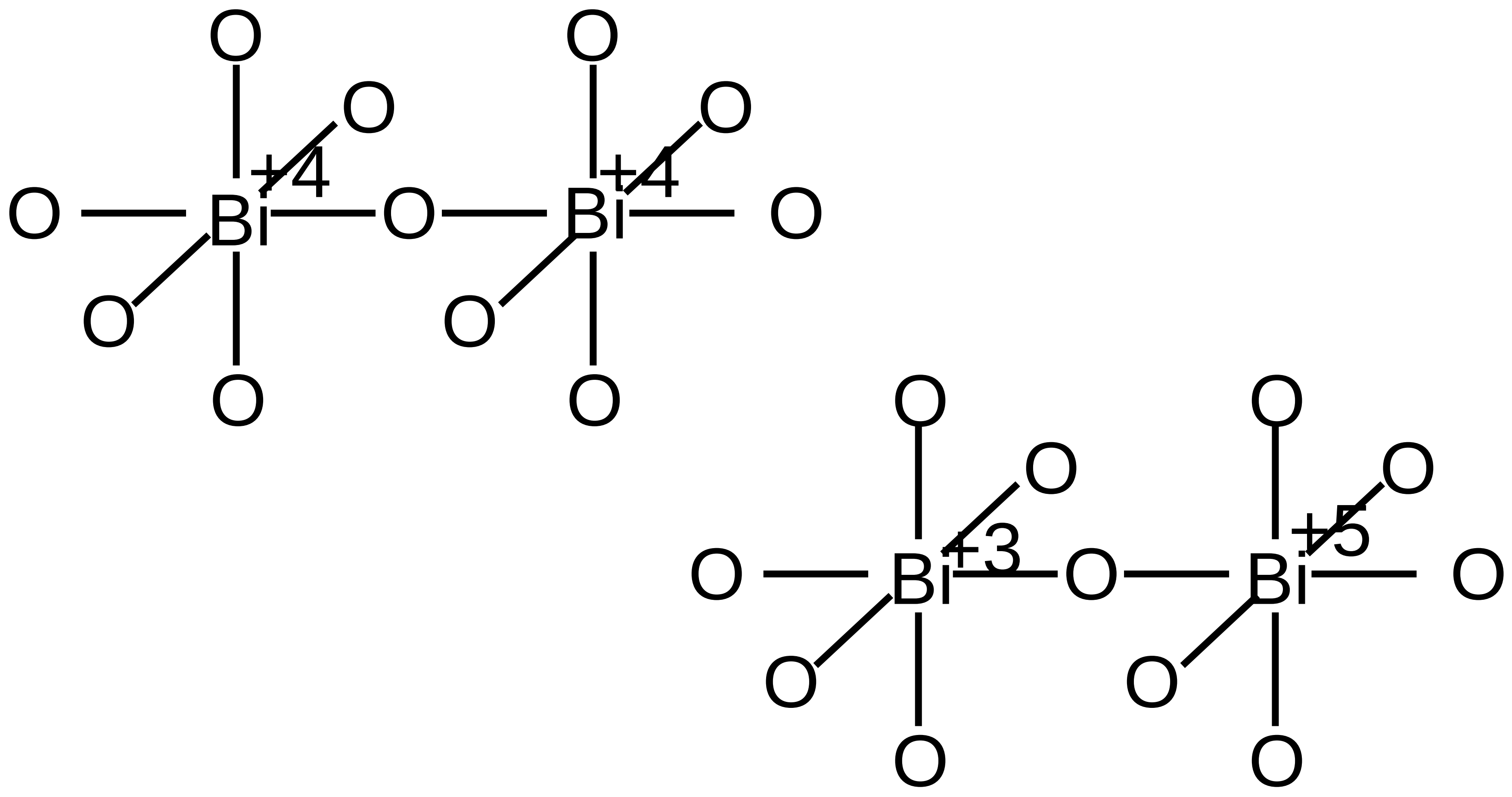
Question

What does it take to have an electronic negative U center?

In the parent BaBiO3 compound the Bi ions exist in a charge disproportionate state which is chemically interpreted a

$$2Bi^{4+} \longrightarrow Bi^{3+} + Bi^{5+}$$





+4
+4
+3
+5

Meregalli and Savrasov, PRB 51 (1998)
LDA + U +linear response
The insulating state BaBiO3 is not correctly described.
For Ba(1-x)K(x)BiO3 the electron-phonon coupling is
not large enough to give Tc~30K.
Need to account for intra-atomic correlations and closed
shell effects.

Question

How do electronic correlations effect the electron-phonon interaction in $Ba_{1-x}K_xBiO_3$?

3. Little-Ginzburg

We need more detailed calculations of the possibility of pairing across a metal-semiconducting interface, or across an interface between a metal and a polarizable layer.

One needs to understand the local field effects, and the spatial dependence of the interaction.

4. Strongly Correlated Strasse

Competing phases :antiferromagnetism, Mott-Hubbard, Stripes, CDW

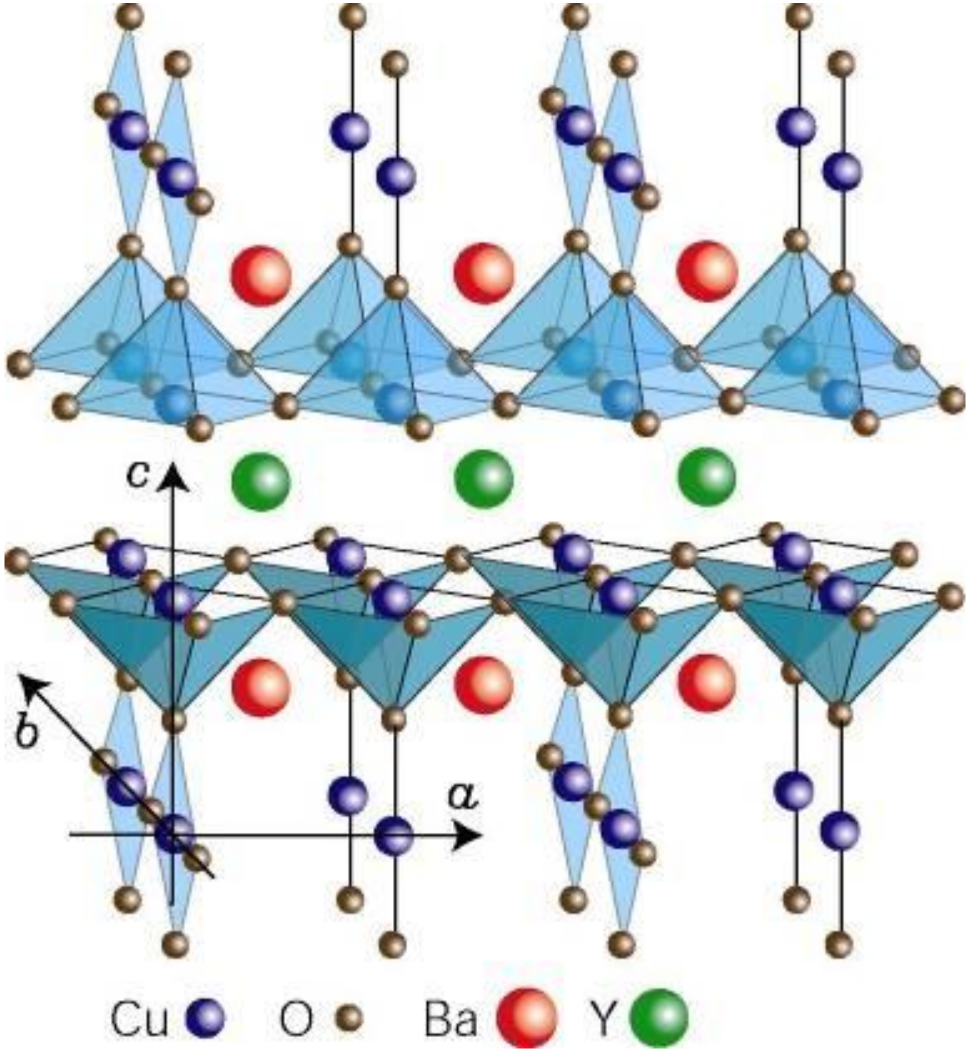
Optimum inhomogenity : pairing strength (gap) versus phase stiffness

4. Strongly Correlated Strasse

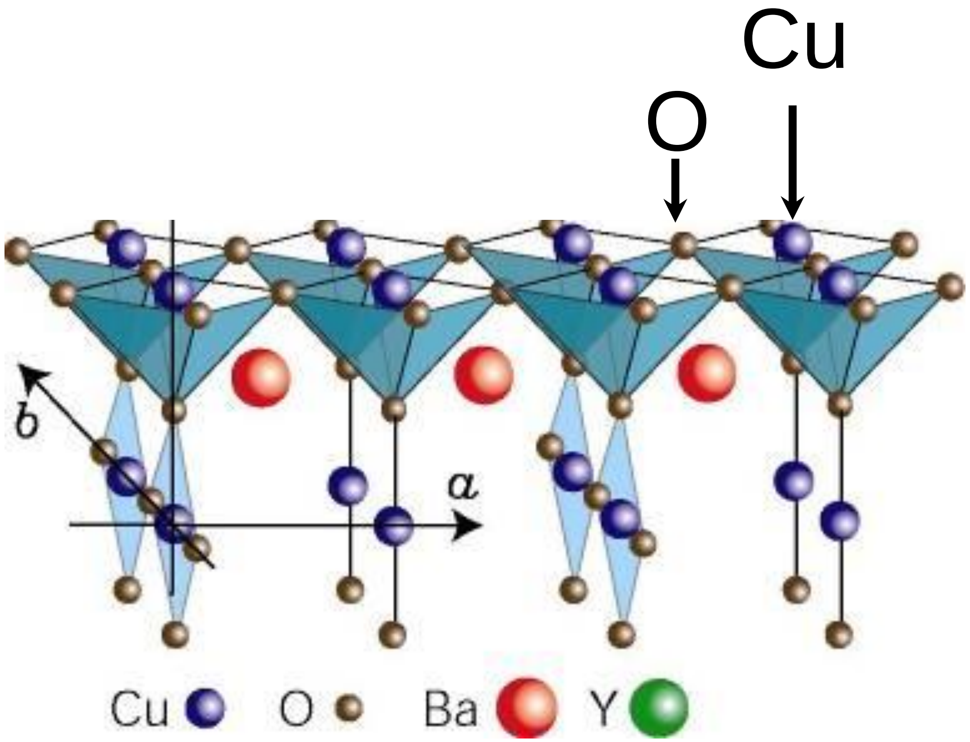
Is the Hubbard model the appropriate model for the cuprates? The undoped cupates are known to be charge-transfer Mott-Hubbard insulators.

What about the long range Coulomb interaction?

What about phonons?

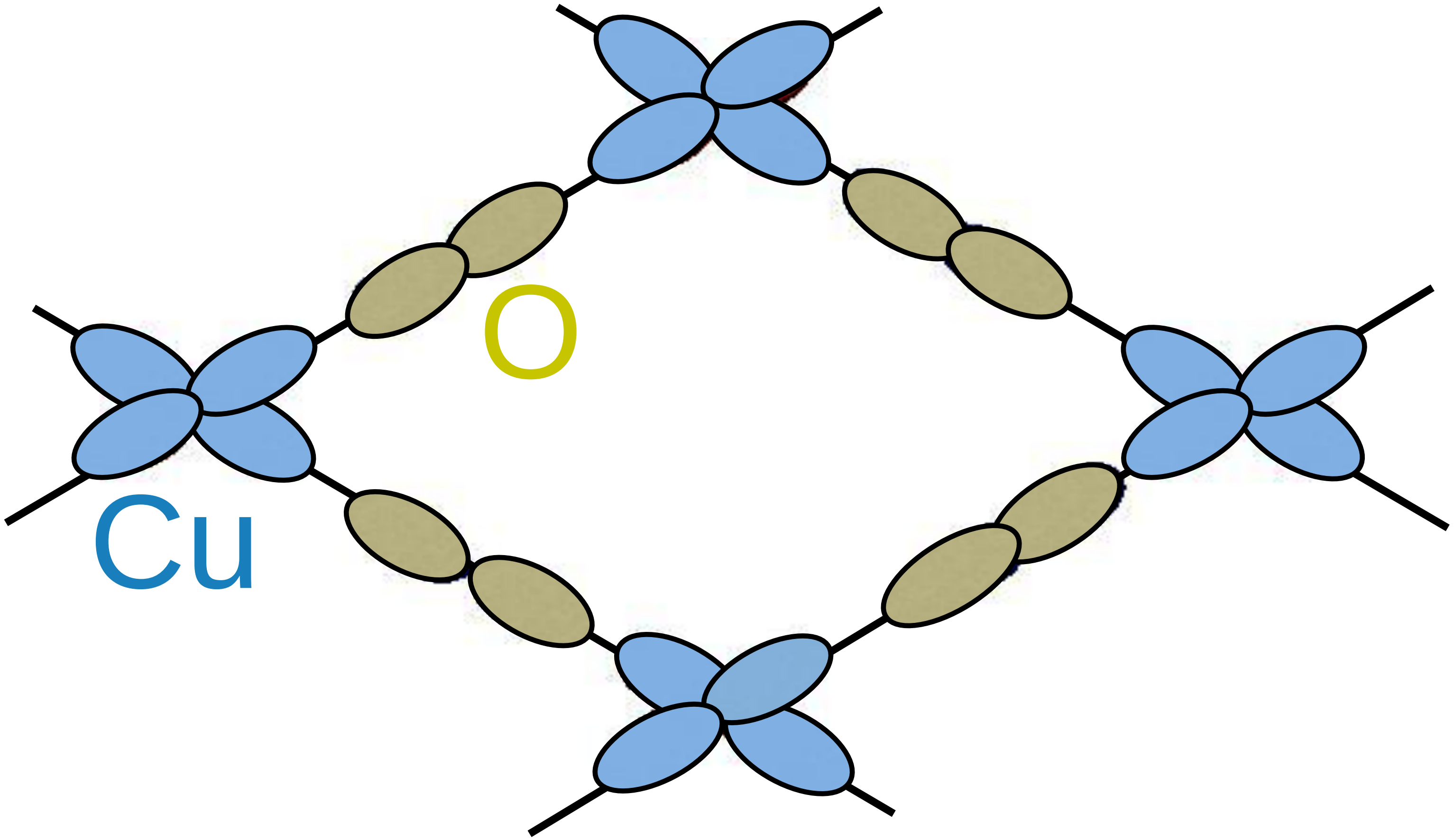


YBCO

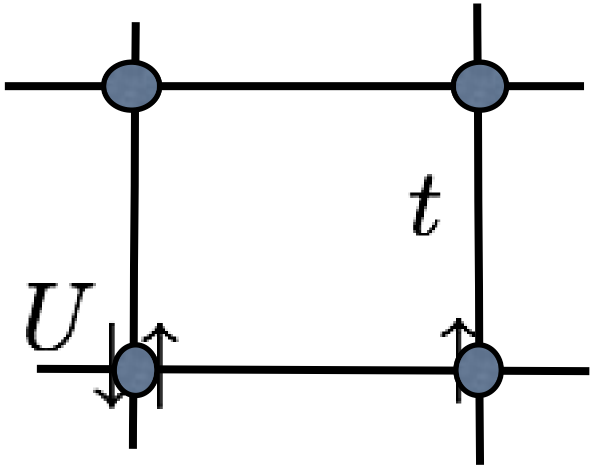


YBCO

The CuO_2 Lattice



The Hubbard Model



$$H=-t\sum_{<i,j>\sigma}(c^\dagger_{i\sigma}c_{j\sigma}+c^\dagger_{j\sigma}c_{i\sigma})+U\sum_i n_{i\uparrow}n_{i\downarrow}$$

It depends upon only two parameters
U/t and the site filling <n>=1-x

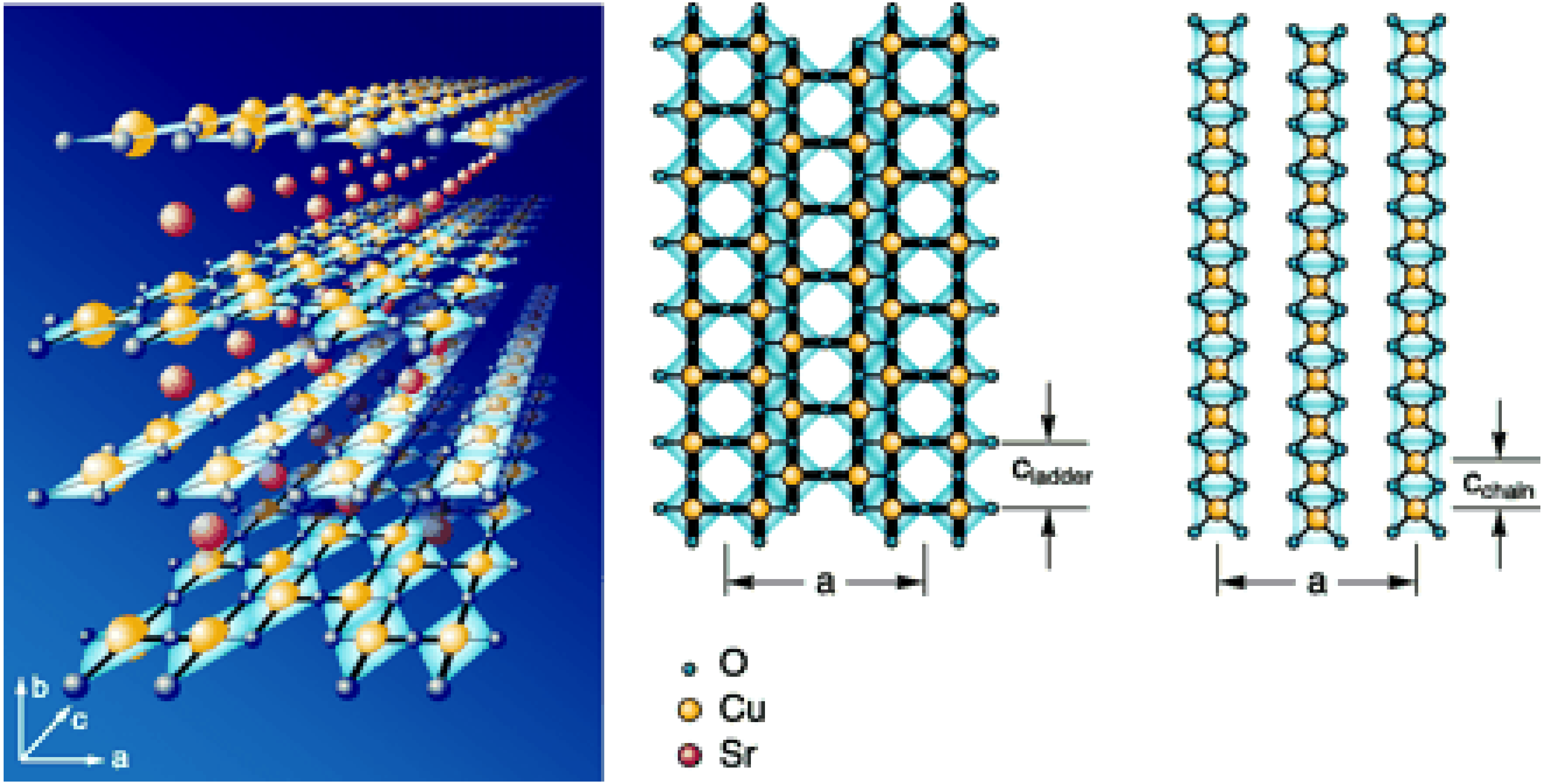
4. Strongly Correlated Strasse

Competing phases :antiferromagnetism, Mott-Hubbard, Stripes, CDW

Optimum inhomogenity : pairing strength (gap) versus phase stiffness

layered cuprates

cuprate ladders



$Sr_{14}Cu_{24}O_{41}$ Ladder Compound

$Sr_{0.4}Ca_{13.6}Cu_{24}O_{41.84}$ Tc~12K at 3 Gpa, Uehara et al 1996

$Ni^+ \quad (3d)^9$

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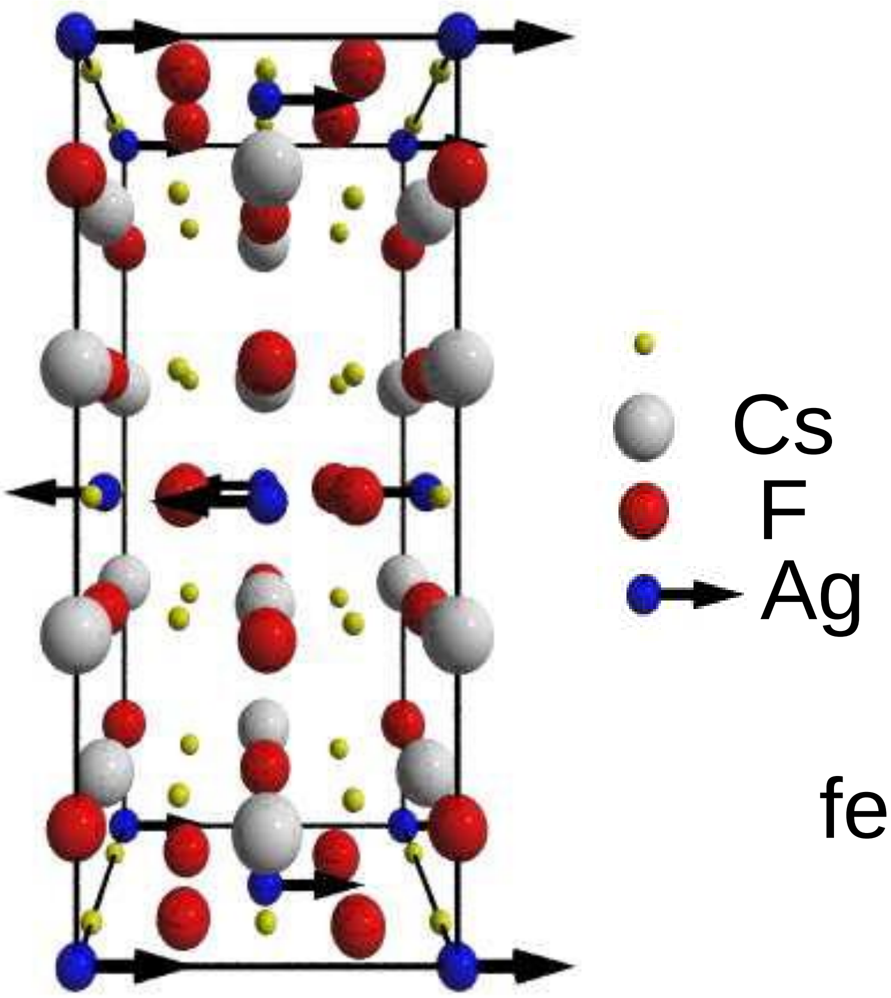
$Ag^{2+} \; (4d)^9 \quad Cs_2AgF_4$ J. Tonner and T. Barnes

$Ni^{+} \quad (3d)^9$

$Ag^{2+} \, (4d)^9 \quad Cs_2AgF_4$ J. Tonner and T. Barnes

Jun Akimitsu
B. Raveau



Ni orbitally ordered

$d_{z^2-x^2}$ $d_{z^2-y^2}$

like K_2CuF_4

ferromagnetic Tc=14K

arXiv:0704.0604

Magnetism in the high-Tc analogue Cs2AgF4 studied with muon-spin relaxation

Authors: T. Lancaster, S.J. Blundell, P.J. Baker, W. Hayes, S.R. Giblin, S.E. McLain, F.L. Pratt, Z. Salman, E.A. Jacobs
J.F.C. Turner, T. Barnes

Comments: 4 pages, 3 figures

Subjects: **Strongly Correlated Electrons (cond-mat.str-el)** layered cuprates

cuprate ladders

$Ni^{+} \quad (3d)^9$

$Ag^{2+} \, (4d)^9 \quad Cs_2AgF_4$

interfaces

5.Microstructure Avenue

Nanoparticles $Ga_{56}(N = 168)$ Tc~160K

$Al_{45}(N = 136)$ Tc~200K

Cu-O 2-leg ladders spingap ~ J/2

2x2 or 4x4 Cu-O clusters

Questions

It would be useful to have additional models which provide more insight into the way in which
the pairing strength and phase stiffness are optimized in various microstructures:

coupled nanoparticles
coupled 2-leg ladders
coupled planes

How does this effect j_c and the H-T phase diagram.

My hope

We will find an s-wave manufacturable Tc=100K superconductor.

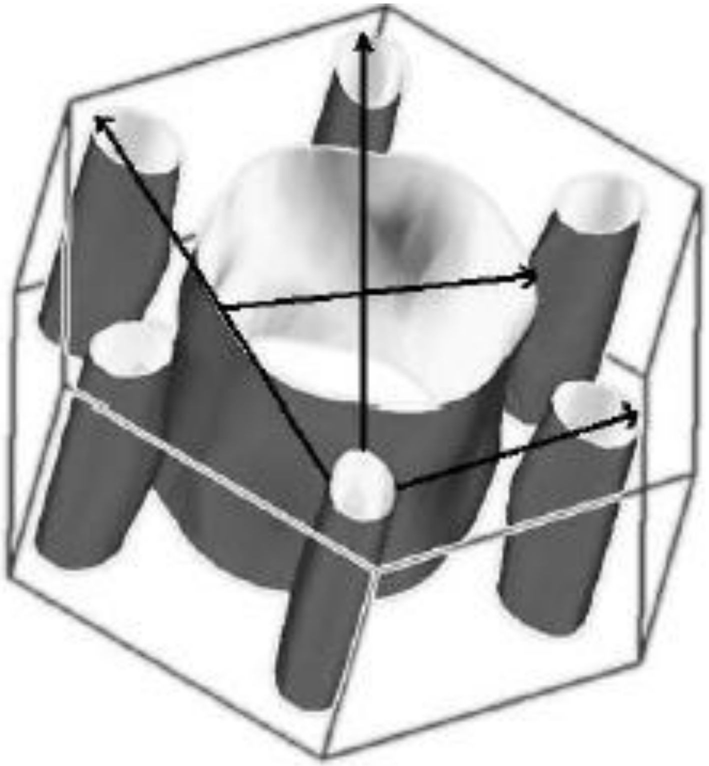
Refrigeration can make it a virtual RTS.

It will have low intermodulation and among other applications will make transmission filters possible.

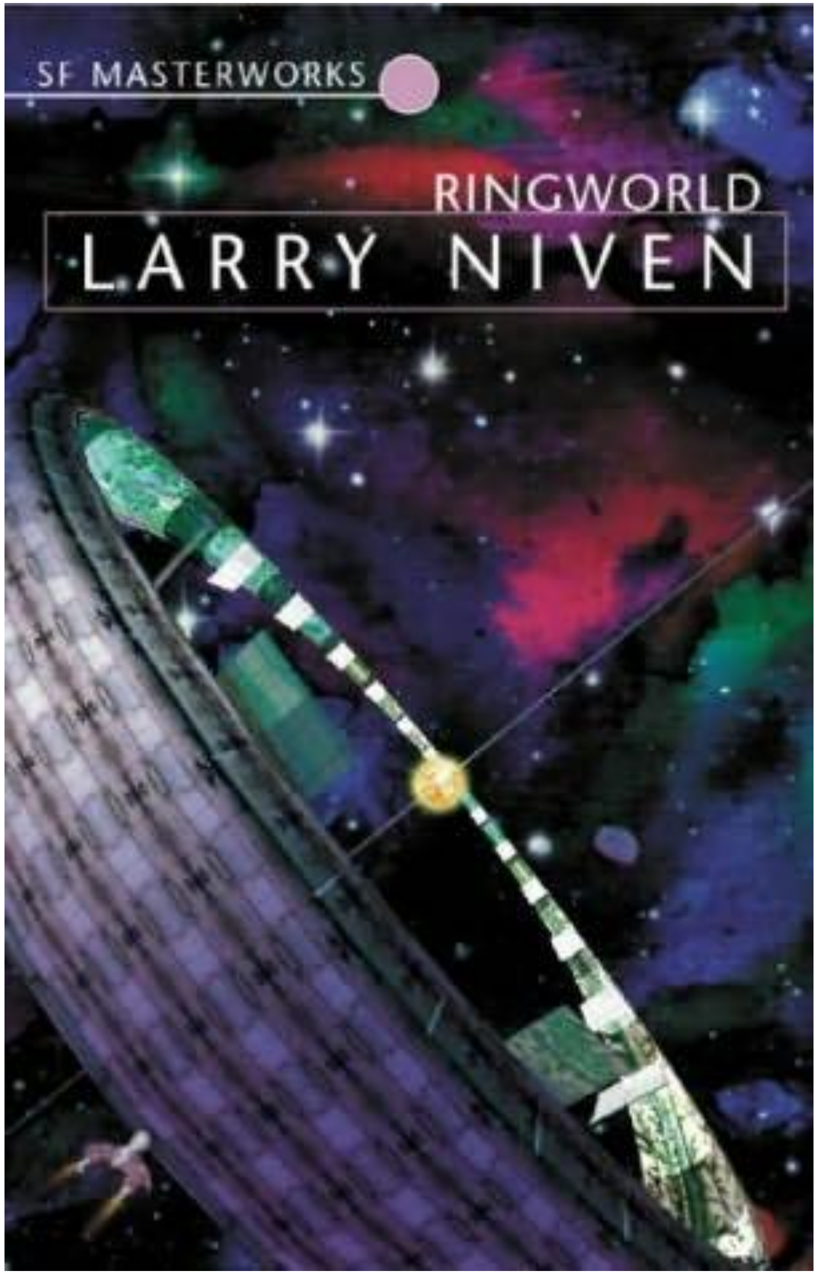
The route that I believe is most promising is the Eliashberg Gate.

The route that I believe is most promising for this is the

Eliashberg Gate



W. Pickett cond-mat/0604074



Series 800 Model 101
Terminator II Judgement Day

Thanks to Harold, Paul ,Horst, Kristian and Mandy for making this a very special week for all of us.

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We also want to thank the Houston International Materials Forum of the University of Houston; the University of Twente and European Union funds; the Norwegian University of Science and Technology (NTNU); and AFOSR’s European Office of Aerospace Research and Development and the AFOSR.

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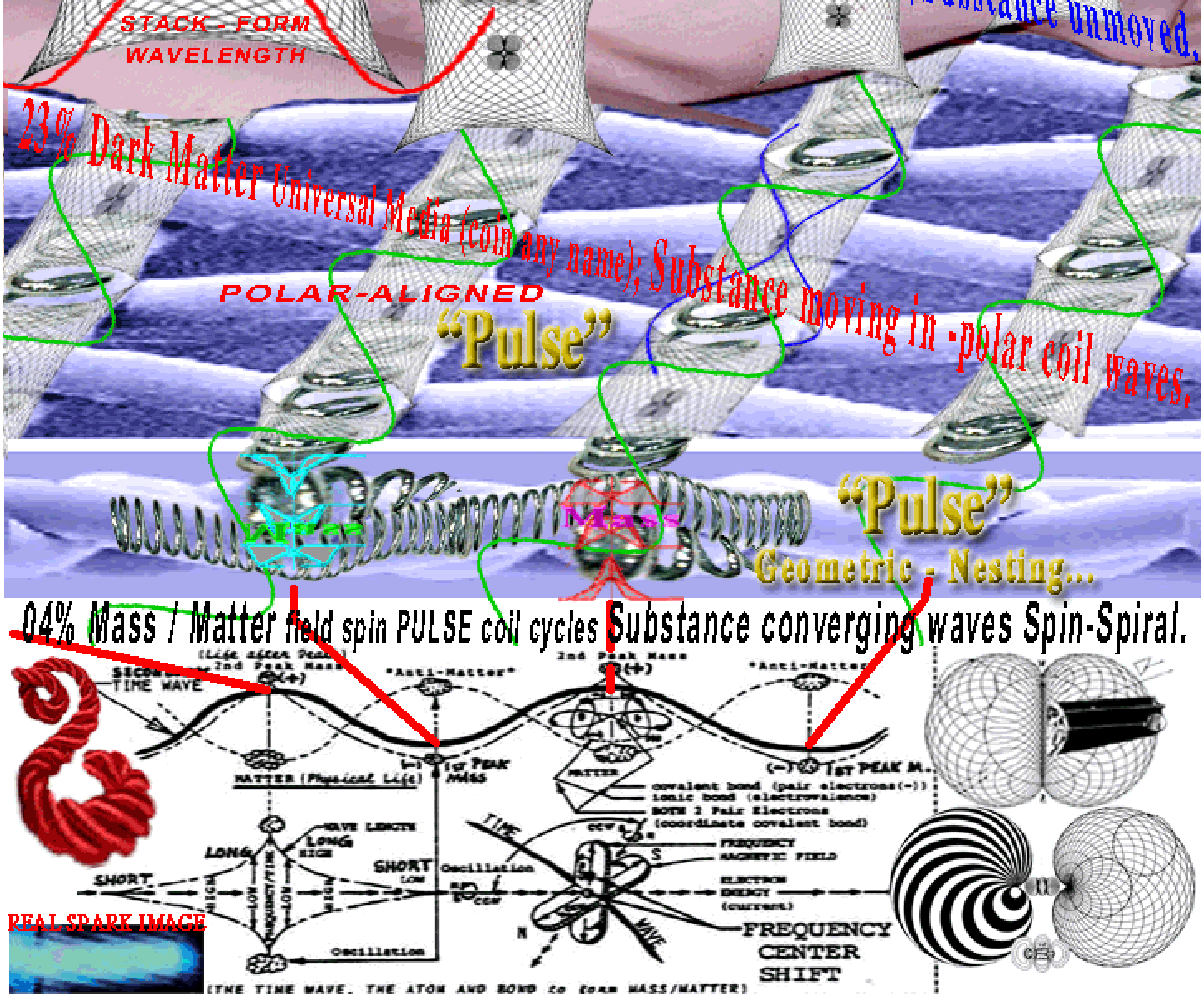

STACK - FORM
WAVELENGTH
substance unmoved,
23% Dark Matter Universal Media (coin any name); Substance moving in polar coil waves.
POLAR-ALIGNED
"Pulse"
Mass
"Pulse"
Geometric - Nesting...
04% Mass / Matter field spin PULSE coil cycles Substance converging waves Spin-Spiral.
(Life after Death)
2nd Peak Mass
(+)
SECOND TIME WAVE
"Anti-Matter"
2nd Peak Mass
(+)
"Anti-Matter"
MATTER (Physical Life)
(-)
1st PEAK MASS
MATTER
(-)
1st PEAK M.
covalent bond (pair electrons(-))
ionic bond (electrovalence)
BOTH 2 Pair Electrons
(coordinate covalent bond)
WAVE LENGTH
LONG
HIGH
LONG
SHORT
HIGH
LOW
FREQUENCY/TIME
LOW
HIGH
SHORT
LOW
Oscillation
TIME
CCW
S
FREQUENCY
MAGNETIC FIELD
ELECTRON
ENERGY
(current)
N
WAVE
FREQUENCY
CENTER
SHIFT
Oscillation
REAL SPARK IMAGE
(THE TIME WAVE, THE ATOM AND BOND to form MASS/MATTER)

Superconductors in popular culture

Superconductivity has long been a staple of science fiction. One of the first mentions of the phenomenon occurred in Robert A. Heinlein's novel *Beyond This Horizon* (1942). Notably, the use of a fictional room temperature superconductor was a major plot point in the *Ringworld* novels by Larry Niven, first published in 1970. Organic superconductors were featured in a science fiction novel by physicist Robert L. Forward. 2

Superconductivity is a popular device in science fiction due to the simplicity of the underlying concept - zero electrical resistance - and the rich technological possibilities. For example, superconducting magnets could be used to generate the powerful magnetic fields used by Bussard ramjets, a type of spacecraft commonly encountered in science fiction. The most troublesome property of real superconductors, the need for cryogenic cooling, is often circumvented by postulating the existence of room temperature superconductors. Many stories attribute additional properties to their fictional superconductors, ranging from infinite heat conductivity (ie thermal superconductivity) in Niven's novels (real superconductors conduct heat poorly, though superfluid helium has immense but finite heat conductivity) to providing power to an interstellar travel device in the Stargate movie and TV series.

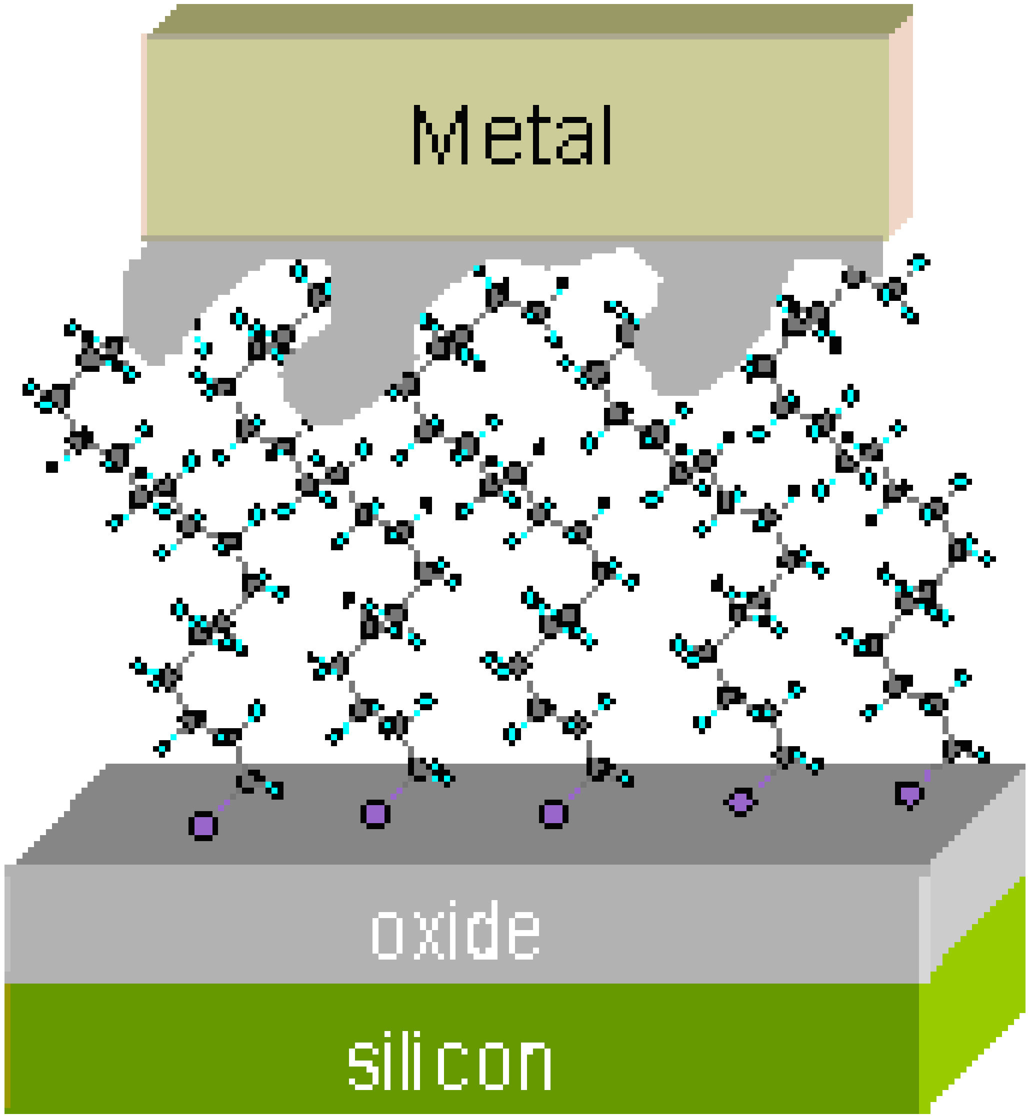
In the movie *Terminator 2: Judgment Day*, the CPU of the T-800 destroyed in Terminator 1 is found to be superconductive at room temperature.

Superconductors are a technology required in the Civilization series (computer game) in order to build the spaceship to Alpha Centauri hence achieving a space victory. Superconductors are also an early technology in another of Sid Meier's games, Alpha Centauri (game)

In the movie "Strangers with Candy", students in a science class build a superconductor made of soup cans.

In the movie "Joe versus the Volcano", an industrialist needs a mineral called bubaru to make superconductors.

Little-Ginzburg



The properties of the Hubbard model are remarkably similar to those observed in the cuprates

- The half-filled <n>=1 Hubbard model is an antiferromagnetic Mott-Hubbard insulator.
- The doped <n>=1-x Hubbard model exhibits a pseudogap, and at low temperatures d-wave pairing and striped states have been found.