UCDAVIS

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Hole Superconductivity Theory - an alternative to BCS Theory

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Hole Superconductivity Theory

Theory by Jorge E. Hirsch

- Interesting and Controversial

- RTS: Most physicists won't agree with Hirsch

- Not as controversial as
Cold Fusion
or
Seady State Universe

- Why new theory needed? Deficiencies of BCS Theory
- Introduction to Hole Superconductivity Theory
- Features of Hole Superconductivity Theory
- Experimental issues

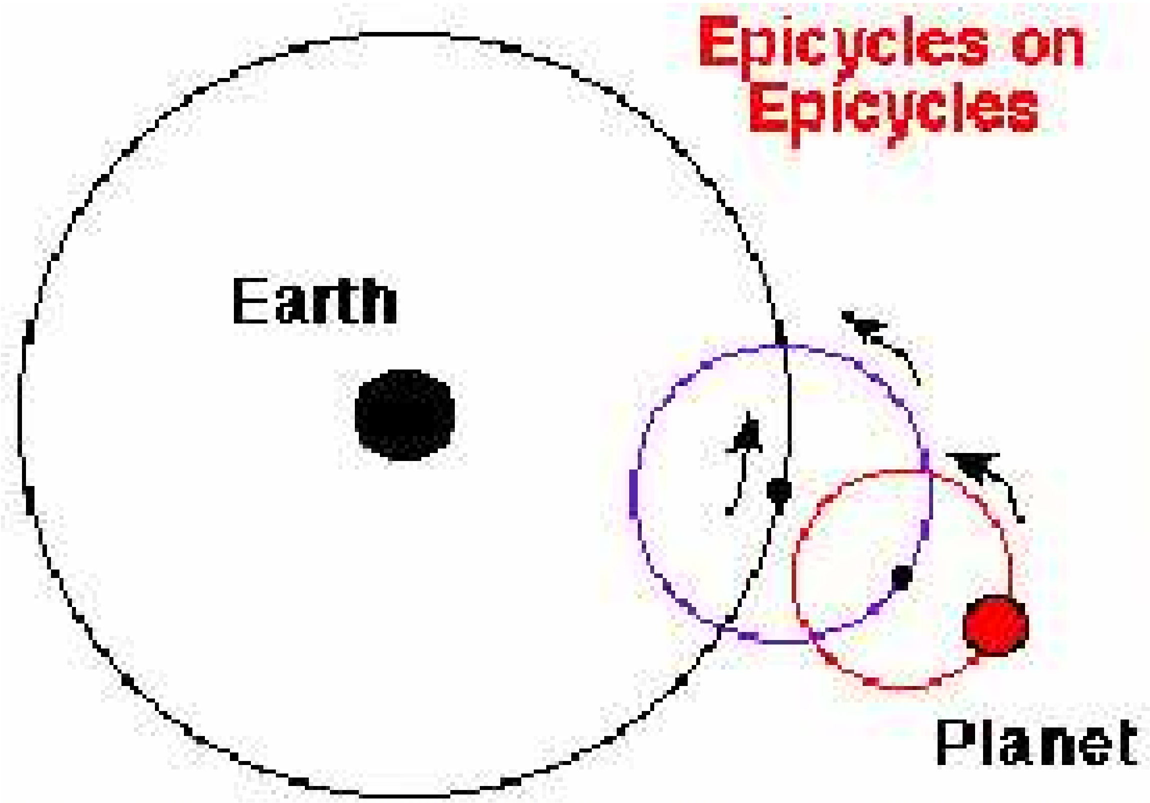
Deficiencies of BCS

1. Lack of transparency

Extremely hard to explain it to a non-physicist and even to a non-solid-state physicist.

Deficiencies of BCS

2. Increasing number of epicycles



Deficiencies of BCS

2. Increasing number of epicycles

Eg:
Isotope effect: considered proof that the electron-phonon interaction responsible for SC. superconductivity, an early observation not easily explained by BCS theory was the
But: Absence of isotope effect in Ru, Os; Inverse isotope effect in U.
Physicists response: more elaborate versions of theory.

Deficiencies of BCS

3. Inability to predict yet ability to post-dict

Eg:

• Superconductivity was predicted for Li at $T_c \sim\geq$ 1K. Found: $T_c \sim$ 0.0004K.

• High T_c was predicted in quasi-one-dimensional materials, based on Little's excitonic mechanism for superconductivity. Not found.

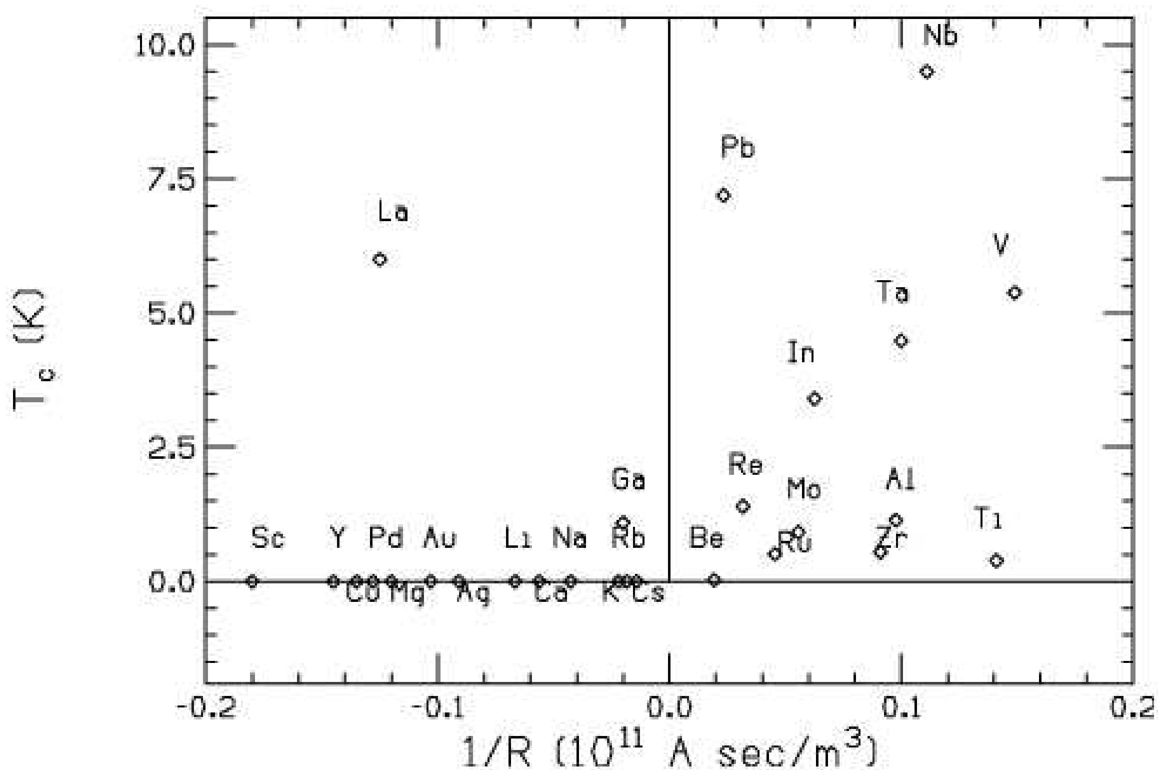
Deficiencies of BCS

4. Blind use of formalism

Deficiencies of BCS

5. Inability to explain Chapnik's rule

Observation: Most of SC elements have positive Hall effect (and therefore charge carriers are positive).
Chapnik's rule: Holes essential for superconductivity.



Deficiencies of BCS

6. Inability to explain the Tao effect

Tao effect:
Superconducting microparticles in the presence of a strong electrostatic field aggregate into balls of macroscopic dimensions.

Deficiencies of BCS

7. Inability to explain the De Heer effect

De Heer effect:
Niobium clusters at low T develop ferroelectric dipole moments. Strong evidence that the electric dipole moment associated with pairing of valence electrons and mirrors superconducting properties of the bulk material.

Deficiencies of BCS

8. Inability to explain rotating superconductors

Rotating superconductor develops inside itself magnetic field

$$\vec{B} = -\frac{m_e}{e}\vec{\omega}$$

e, m_e - charge, mass of SF charge carrier.

- $\vec{B}$ parallel $\vec{\omega} \Rightarrow e < 0 \Rightarrow$ charge carriers e^-'s, not holes. But in normal state carriers in these materials are holes.
- m_e and e in equation are mass and charge of **free electron**.
- $\vec{B}$ the same whether a superconductor put into rotation or a rotating normal metal cooled into the SC state.

Deficiencies of BCS

9. Inability to explain the Meissner effect

Questions:

- How electrons near surface acquire the superfluid velocity needed to screen the magnetic field in the interior?
- How angular momentum conserved?

Deficiencies of BCS

10. Deviation from Occam's razor

Occam's razor:

• Make as few assumptions as possible.

Alternatively:

• The simplest solution to a problem preferable to more complicated solutions.

• To explain all superconductors known today needs many different mechanisms and fundamentally different physical assumptions.

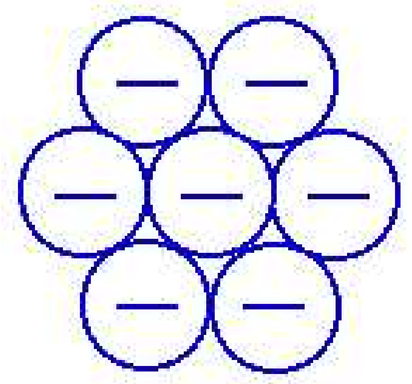
Hole Superconductivity Theory

Hirsch:
Electron-hole asymmetry is the key to superconductivity;

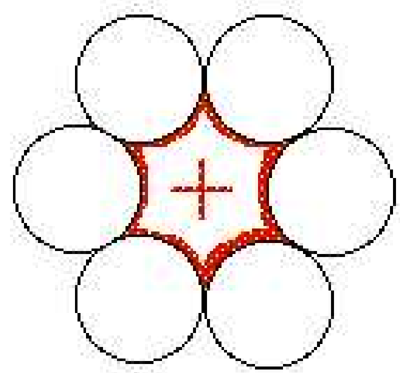
Electrons and holes differ.

Hole Superconductivity Theory

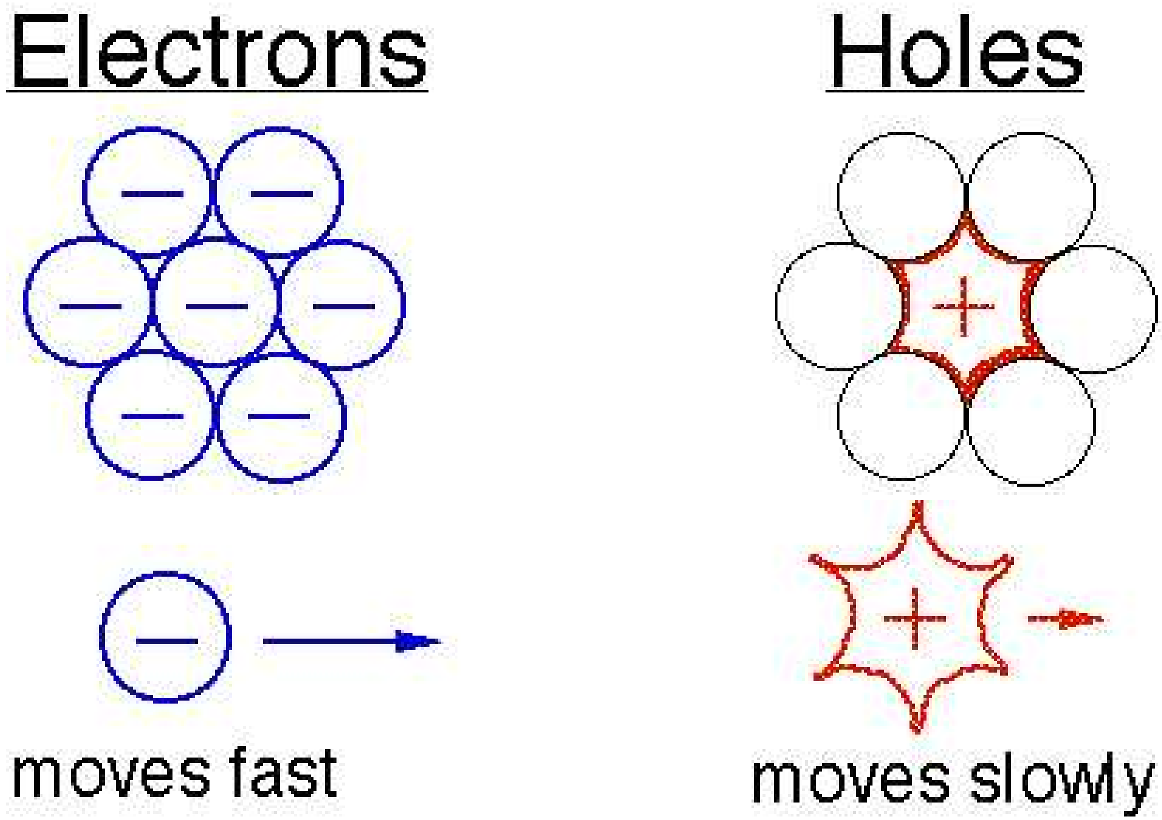
Electrons



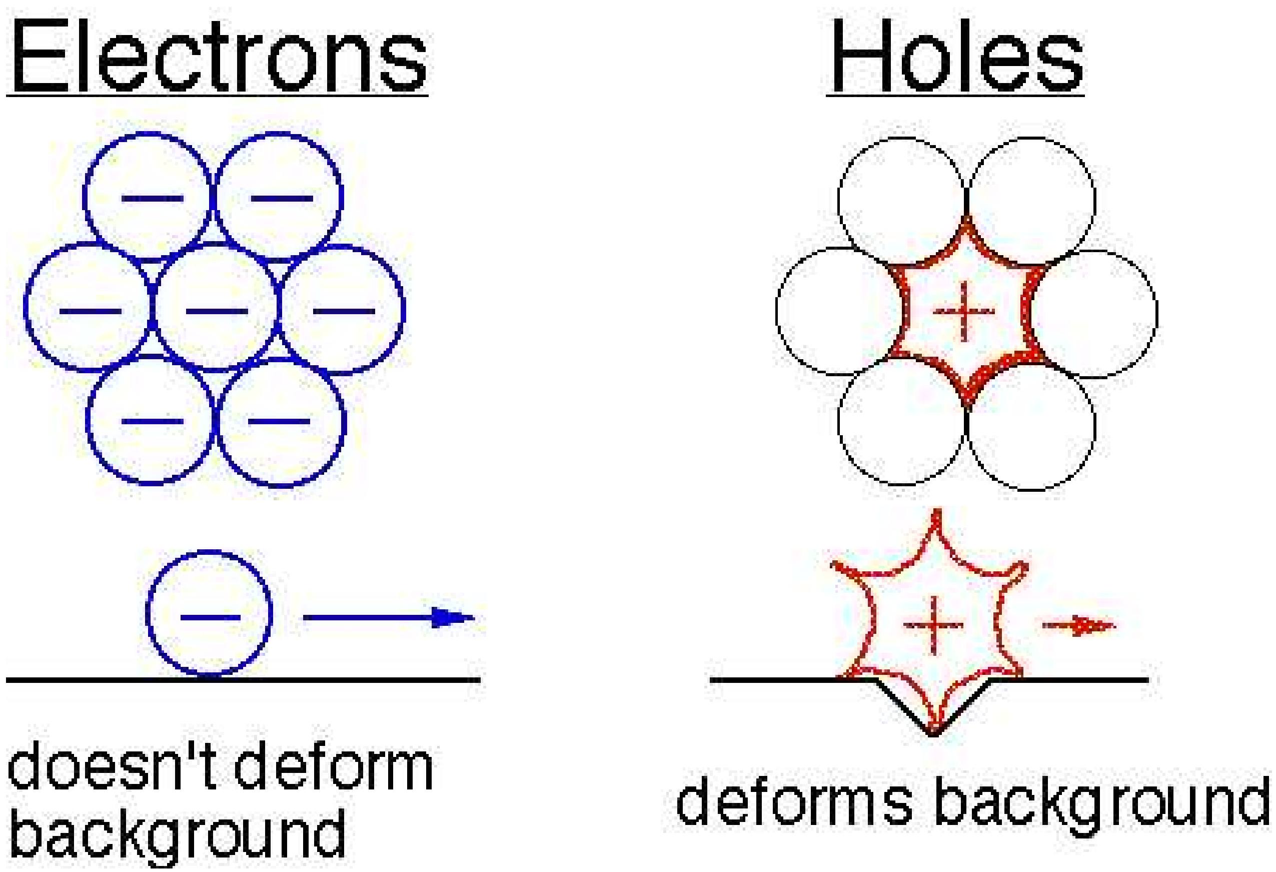
Holes



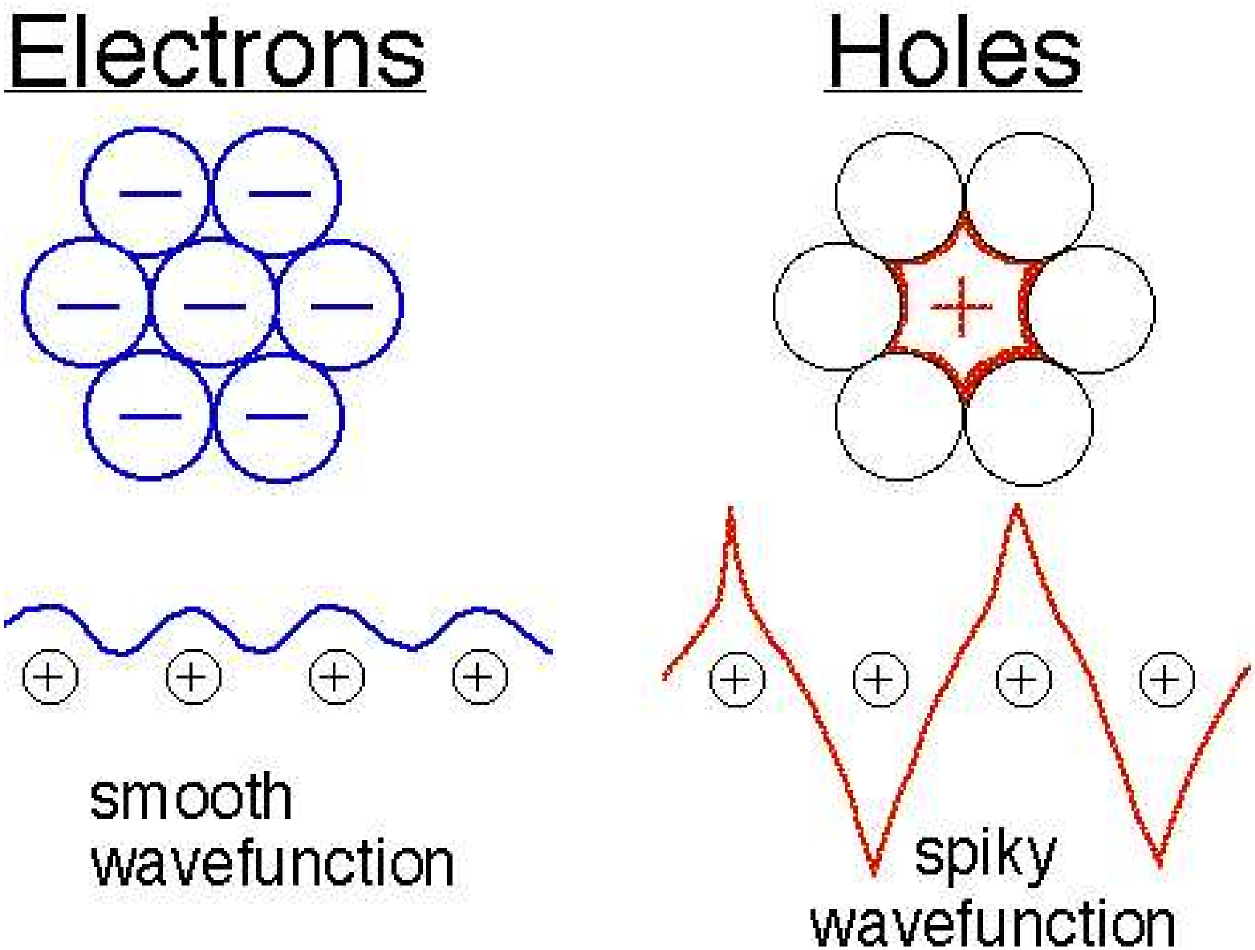
Hole Superconductivity Theory



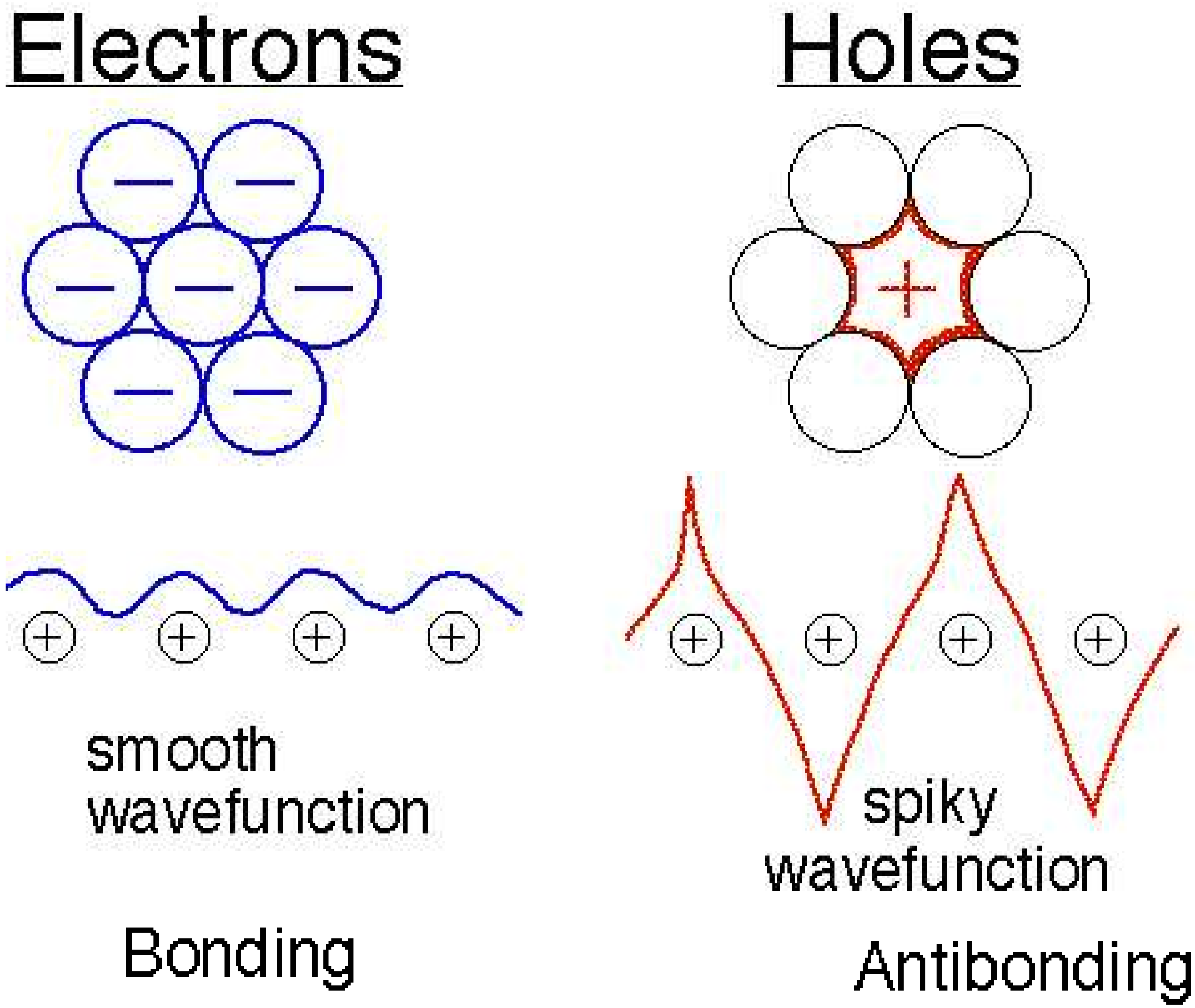
Hole Superconductivity Theory



Hole Superconductivity Theory



Hole Superconductivity Theory



Hole Superconductivity Theory

Hole superconductivity theory:

- Superconductivity can only occur when 'hole' carriers exist in the normal state of a metal.
- A hole in a full band has difficulty propagating due to the disruption it causes in its environment.
- Superconductivity occurs due to pairing of hole carriers, and is driven by the fact that paired holes can propagate more easily (have a smaller effective mass) than single holes.
- In contrast, single electrons can move easily and so they don't pair.
- 'Dynamic Hubbard models' describe the different physics of electron and hole carriers in metals.
- The reason for the increased mobility of holes upon pairing is that they 'undress' when they pair, and turn into electrons.This leads to a new understanding of superconductors, that a superconductor is a giant atom .

Hole Superconductivity Theory

Hamiltonian

$$H = \sum_{k,\sigma} \epsilon_k c^\dagger_{k\sigma} c_{k\sigma} + \sum_{kk'q} V(q) c^\dagger_{k+q\uparrow} c^\dagger_{k'-q\downarrow} c_{k'\downarrow} c_{k\uparrow}$$

$$+ \sum_{kk'\nu} I^{\nu}_{k-k'} c^\dagger_{k'\sigma} c_{k\sigma} (b_{k'-k,\nu} + b^\dagger_{k-k',\nu})$$

$$+ \sum_{q\nu} \omega_\nu b^\dagger_{q\nu} b_{q\nu}$$

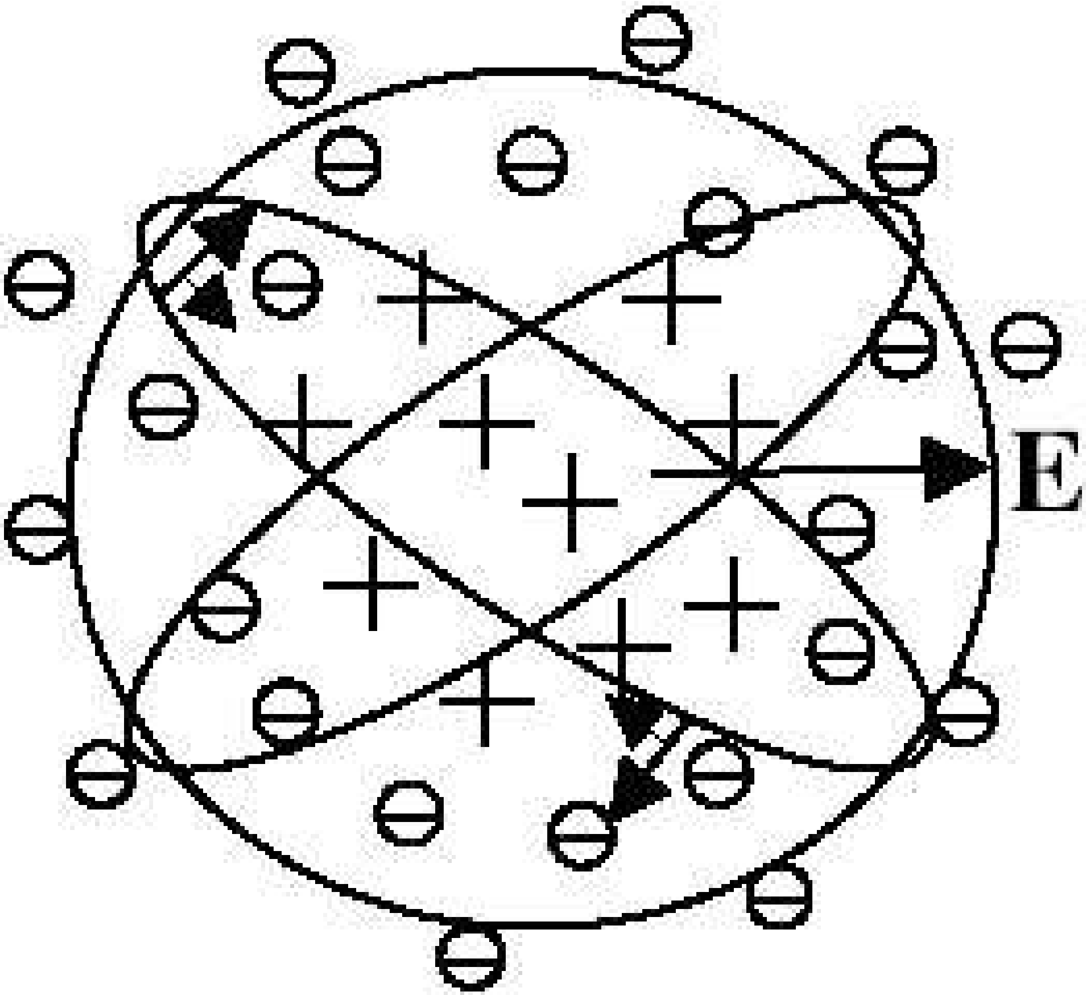
$c^\dagger_{k\sigma}$ creates hole in filled outer shell.
$V(q) = 4\pi e^2/q^2$ - Coulomb interaction between holes.
Third term - interaction between hole and filled outer shell.
$b^\dagger_\nu$ creates excitation in filled outer shell,

Hole Superconductivity Theory

How SC works:

- Holes pair
- When holes pair, they undress
- When holes undress, they turn into electrons
- These electrons behave as electrons in giant atoms

Hole Superconductivity Theory



Superconductor as a giant atom:
Electrons pushed out of interior towards surface.
Electric field pointing out exists inside superconductor.
Some electrons spill outside surface.

Hole Superconductivity Theory

If Hole Superconductivity Theory correct $\Rightarrow$

- Electron-phonon interaction irrelevant to superconductivity
- BCS theory is incorrect
- London theory is incorrect.

Hole Superconductivity Theory

Explains the Meissner effect

Hole Superconductivity Theory

Predicts Spin Meissner effect:
Macroscopic spin current flows within a London penetration depth λ_L of the surface of superconductors in the absence of applied external fields, with carrier density = the superfluid density and carrier speed $v = \hbar/(4m_e\lambda_L)$ (m_e =bare electron mass).

Features of Hole Superconductivity Theory

(1) It applies to all superconducting materials.

(2) Electron-hole asymmetry is the key to superconductivity; hole carriers in the normal state are necessary for superconductivity.

(3) Electron-phonon interaction does not cause superconductivity; pairing is driven by a purely electronic mechanism associated with kinetic energy lowering.

(4) Material characteristics favorable for high T_c are:

(i) transport in the normal state dominated by hole carriers;

(ii) excess negative charge in the substructures (e.g. planes) where conduction occurs.

Features of Hole Superconductivity Theory

(5) The gap function versus energy has a slope of universal sign, giving rise to asymmetry in tunneling experiments of universal sign.

(6) Superconductors expel negative charge from their interior towards the surface in the transition to superconductivity.

(7) London electrodynamic equations are modified. Macroscopic charge inhomogeneity and a macroscopic outward pointing electric field exist in the interior of superconductors. Applied electric fields are screened by the superfluid over a London penetration depth distance λ_L rather than over the much shorter Thomas Fermi distance.

Features of Hole Superconductivity Theory

(8) A macroscopic spin current flows within a London penetration depth of the surface of superconductors, a kind of zero point motion of the superfluid.

(9) The spin-orbit interaction plays a fundamental role in superconductivity.

(10) Superfluid holes reside in mesoscopic orbits of radius $2\lambda_L$ and carry orbital angular momentum $\hbar/2$. The theory offers transparent explanations for the Meissner effect, the Tao effect, the puzzles of rotating superconductors, Chapnik's rule, and the variation of T_c along the elements in the transition metal series.

Hole Superconductivity Theory: Experimental Issues

Is Hole Superconductivity Theory correct?

The best way to answer would be to check some of Hirsch's predictions:

Spin Meissner effect

• Electron-positron pair production in SC above critical size

For superheavy atoms or molecules spontaneous electron-positron pair production will occur, when the binding energy of a K-shell electron becomes equal to twice its rest mass.
$\Rightarrow$ pair production for superconductors of large size.

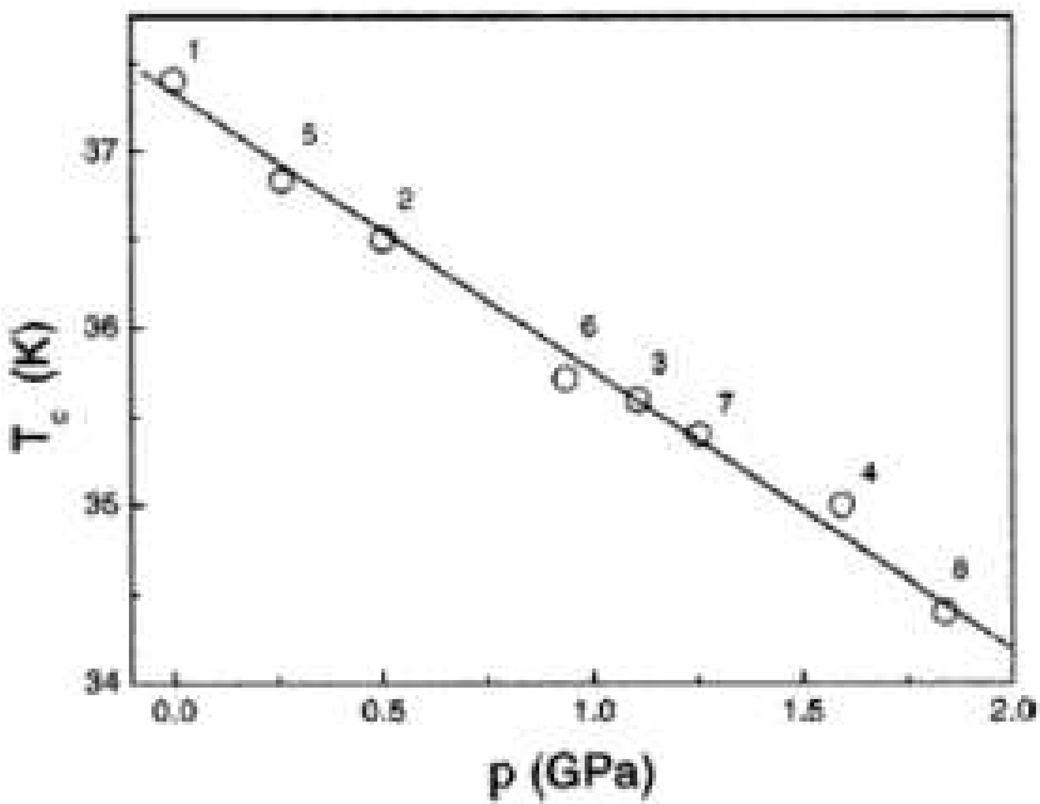
Eg, Hirsch gives for Nb:
$R_c = 3.33 \times 10^5 \lambda_L \quad = 1.33 cm.$

• Change of color in some superconductors when they become superconducting.

• MgB_2 superconductivity, $T_c = 39K$.

A. V. Narlikar, Frontiers in superconducting materials, Birkhäuser, 2005

Hole superconductivity theory:
Increase of T_c with pressure, if pressure reduces $B-B$ distance.
However, experiments show $dT_c/dP < 0$.



• Shen (1993), Hardy (1993).

Hirsch:

Recent experimental claims of large in-plane anisotropy in the gap function (Shen et al, 1993) and of intrinsic linear behavior in the London penetration depth versus temperature (Hardy et al, 1993) would rule ot the model out, if confirmed.

Referenced papers:

Z.-X. Shen, D. S. Dessau, B. O. Wells, D. M. King, W. E. Spicer, A. J. Arko, D. Marshall, L. W. Lombardo, A. Kapitulnik, P. Dickinson, S. Doniach, J. DiCarlo, T. Loeser, and C. H. Park, PRL 70, 1553 (1993), "Anomalously large gap anisotropy in the a-b plane of $Bi_2Sr_2CaCu_2O_{8+\delta}$"

W. N. Hardy, D. A. Bonn, D. C. Morgan, Ruixing Liang, and Kuan

Zhang, PRL 70, 3999 (1993): $\lambda(T)$ from 1.3 K to T_c in very high quality single crystals of $YBa_2Cu_3O_{6.95}$: strong linear term.

Summary

• Presented Hirsch's ”Hole Superconductivity Theory”, an alternative to the BCS theory.

• Hole Superconductivity Theory makes a few interesting predictions.

• Hole Superconductivity Theory needs experimental confirmation / disproval.
Some experiments give negative results. Not conclusive yet.