Emergence of quantum phases in novel materials

SUPERCONDUCTIVITY II

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BIBLIOGRAPHY (BOOKS)

Collection of reviews

• Conventional SPC “Superconductivity” Edited by Parks. 1968.

• Conventional and unconventional SPC “Superconductivity” 2008 (Fe SPC not included)

“Many-body physics” Piers Coleman

“Introduction to superconductivity” Tinkham

SPC history:

“Superconductivity: a very short introduction” S. Blundell
OUTLINE

- Superconductivity
  - Properties (zero resistivity, Meissner effect)
  - Understanding (pairing, BCS, Ginzburg-Landau)
  - Electron-phonon interaction (conventional superconductivity)

- Unconventional superconductivity (unsolved)
  - What are the new issues.
  - What are the proposals.
1911 Discovery

1986 High T_c, Cuprates

2008, high T_c Fe superc.

www.ccas-web.org/
MATTHIAS’S RULES?

Theory predicted superconductivity in semiconductors. Measured shortly after in SrTiO$_3$. $T_c=0.3$K

Cohen RMP 36, 240 (1964); PRL 12, 474 (1964)

High $T_c$

Cuprates

Fe-superconductors

AF supercond.

Heavy fermions

Oxides

Insulators

Magnetism

AF+SPC

Coexistence

Eur. Phys. JB 21, 175

Organics

FM superconductors

UNCONVENTIONAL SUPERCONDUCTORS

AF supercond.
Heavy fermions

Oxides
Insulators
Magnetism

AF+SPC
Coexistence

High $T_c$
Cuprates

Fe-superconductors

Not driven by conventional phonons. Is BCS valid?

AF+SPC
Coexistence

Eur. Phys. JB 21, 175
UNCONVENTIONAL SUPERCONDUCTORS

The “normal” state is more complicated

• Proximity or coexistence with magnetism
• Strong correlations.
  • Competing orders (stripes).
• Low dimensionality, anisotropies.
UNCONVENTIONAL SUPERCONDUCTORS

The superconducting state is different

The pairing function $\Delta_k$ may

- Be non-isotropic (including nodes, sign changes)
- Have a finite orbital momentum
- Be spin-triplet
- High superconducting $T_c$
- $\lambda >> \xi$ (type II)
- Anisotropies

\[
\frac{2\Delta}{k_B T_c} >> 3.53
\]
Many theories.
2 distinct approaches to the problem:

- Stay within BCS but a new pairing (glue) mechanism is needed (maybe spin fluctuations, some kind of electron-phonon interaction).

- Start from the Mott state (no boson exchange required) and see how to gain energy from pairing
  - Resonating valence bonds
  - Kinetic energy driven
  - Quantum criticality...
Many theories.
2 distinct approaches to the problem:

• Stay within BCS but a new pairing (glue) mechanism is needed (maybe spin fluctuations, some kind of electron-phonon interaction).

A: We know how to deal with it.
D: Usually there is no Fermi surface. Note: Fe superconductors are not Mott insulators; their AF state is a metal.
Many theories.  
2 distinct approaches to the problem:

- Start from the Mott state
  - Resonating valence bonds
  - Kinetic energy driven
  - Quantum criticality...

A: It seems, in principle, more self-consistent.  
D: We need to properly treat the Mott state first!!
Is it possible to have a universal theory of superconductivity?
Assume BCS is valid for non-conventional superconductors. Then we need some attractive interaction but we don’t have the help of phonons anymore! Moreover, we have a very strong electron-electron repulsive interaction. Is there a way around it??
PAIRING SYMMETRY

\[ \psi(\vec{r}_1s_1, \vec{r}_2s_2) = \varphi(\vec{r}_1, \vec{r}_2) \chi(s_1, s_2) \]

Spatial Spin

Pair wavefunction must be antisymmetric

Spin singlet \( \rightarrow \) even parity orbital wave function s, d
Spin triplet \( \rightarrow \) odd parity orbital wave-function p, f

Superfluidity in \(^3\)He is p-wave
SUPERFLUIDITY IN $^3$HE (1972) $T_c=2.7$ mK

Pairing cannot be mediated by the lattice. Nuclear forces are strongly repulsive in the core $\rightarrow$ no s-wave possible. Need of wavefunctions that vanish at $r\rightarrow0$.

One possibility is mediation by ferromagnetic spin fluctuations: FM paramagnons (FM fluctuations suppress s-wave and enhance p-wave pairing).
SUPERFLUIDITY IN $^3$HE

Attractive interactions by ferromagnetic fluctuations:

FM clouds are formed which attract the $^3$He quasiparticles (something like magnetic polarons instead of lattice polarons)

Blundell’s book
High angular momentum pairing was proposed for $^3$He as a way to overcome the short range repulsion (Pitaevskii 1959).

What about non-conventional superconductors?

Mostly singlet pairs with mainly d-wave symmetry, but in iron superconductors both s and d are postulated. Triplet: Ruthenates (p-wave).
$S$-WAVE

Gap equation from BCS (T=0)

\[
\Delta_k = -\frac{1}{\Omega} \sum_{kk'} V_{kk'} \frac{\Delta_{k'}}{2E_{k'}}
\]

For $V_{kk'}$ constant and attractive: isotropic gap $\Delta_k = \Delta$

$s$ wave gap
(spherical symmetry)

More generally, $s$-wave gap may be anisotropic with no sign changes.

D-WAVE

Gap equation from BCS (T=0)

\[ \Delta_k = -\frac{1}{\Omega} \sum_{kk'} V_{kk'} \frac{\Delta_{k'}}{2E_{k'}} \]

Repulsive \( V_{kk'} \) ↔ Anisotropic \( \Delta_k \) with sign change!

\[ \text{sign}(\Delta_k) = -\text{sign}(V_{k,k'})\text{sign}(\Delta_{k'}). \]

For instance, d-wave

\[ \Delta_k = \Delta_0 \cos(2\phi) \]

The gap has nodes and sign changes

An anisotropic pair potential leads to an anisotropic gap

\[ V_{kk'} = -V_0 \gamma_k \gamma_{k'} \]

\[ \Delta_k = \gamma_k \Delta_0 \]
GAP SYMMETRIES...


Hirshfield et al. 1106.3712

nodal $s_{\pm}$

$d$

http://www.qm.phy.cam.ac.uk/teaching/
SINGLET-TRIPLET

From Knight shift experiments

Singlet (spin quenching at low T)

PRB 63, 060507 (2001)
NODES VERSUS NODELESS

s-wave pairing

\[ N_{\text{exc}}(\varepsilon) \]
\[ C_{\text{el}} \sim e^{-\Delta/k_B T} \]

Nodal point

d-wave pairing

\[ N_{\text{exc}}(\varepsilon) \]
\[ C_{\text{el}} \sim T^2 \]

http://www.qm.phy.cam.ac.uk/teaching/
Without nodes: activated behavior ($\lambda$, specific heat...)  
With nodes: power law behaviors

Gap without nodes

London penetration length within BCS

\[
\frac{\Delta\lambda(T)}{\lambda(0)} \sim 3.33 \left( \frac{T_c}{T} \right)^{1/2} \exp(-1.76T_c/T)
\]

Gap with nodes

Power law dependencies

Pb$_{0.95}$Sn$_{0.05}$  
PRL 70, 3999 (1993)  
(no phase information)
ARPES

TUNNELING SPECTROSCOPY

Nature Physics 10, 483–495 (2014)

(no phase information)
SENSITIVITY TO THE PHASE: JOSEPHSON EFFECT

\[ I_s = I_c \sin \Delta \varphi \]

Calculated critical current

PRL 71, 2134 (1993)

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SOME TYPICAL PHASE DIAGRAMS

Heavy fermions

Cuprates

Fe–superconductors

Organics

In common: (AF)magnetic phases

Nature 468, 184–185

HEAVY FERMIONS (1979)

“Our experiments demonstrate for the first time that superconductivity can exist in a metal in which many-body interactions, probably magnetic in origin, have strongly renormalized the properties of the conduction-electron gas.”

PRL 43, 1892 (1979)

Coexisting AF + SPC

Reentrant SPC due to competition with Kondo

Quantum criticality

Nat. Phys. 4, 186

PRL 43, 1892 (1979)
Proximity of quantum critical point can lead to coexistence

Layers of CuO$_2$. Different related structures. But note!: SPC requires coherence in 3dim.

Highest Tc 134K (at ambient pressure). Tc increases with number of CuO$_2$ planes in the unit cell (up to n=3).

Pairs were found to be singlets.

d-wave pairing was proposed in the cuprates early on.


Undoped cuprates are Mott insulators and AF ($\pi, \pi$).
PSEUDOOGAP

Spin quenching sets up at $T^*$.

Origin?: spin-singlet formation (Anderson), pairing with short range order (preformed pairs), antiferromagnetic fluctuations, charge density wave

Is it due to fluctuations or is it a new phase (with a related broken symmetry)? Transition or crossover?
PSEUDOGAP

In other words:
Is it a precursor or a competing phase?

Norman, cond-mat:0507031
Many different families discovered, all sharing a Fe plane


Cuprates are not the only high Tc superconductors!
Fe-As or Fe-Se planes

Paglione and Greene, Nat. Phys. 6, 645 (2010)
Highest TC in Fe Superconductors

Single layer FeSe on SrTiO$_3$

**FE BASED SUPERCONDUCTORS**

Differences with cuprates:
- The AF state is metallic (not Mott insulator): Hund metal.
- Multiorbital system (more than 1 gap possible)
- SPC can be achieved without chemical doping.
- More 3dim (less anisotropy in c-direction)

Proposed mechanisms for superconductivity
- Spin fluctuations (\(\pi,0\))
- Orbital fluctuations

Gap symmetry

<table>
<thead>
<tr>
<th>Family</th>
<th>Full gap</th>
<th>Highly anisotropic</th>
<th>Strong nodal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1111</td>
<td>PrFeAsO(_{1-y})[52K] [293] SmFeAs(O,F)[55K] [295]</td>
<td>LaFeAs(O,F)[26K] [214] NdFeAs(O,F) [214]</td>
<td>LaFePO[6K] [203, 204, 294]</td>
</tr>
<tr>
<td>122</td>
<td>(Ba,K)Fe(_2)As(_2)[40K] [146, 236, 296, 242] Ba(Fe,Co)(_2)As(_2) [OP,23K] [238, 208]</td>
<td>Ba(Fe,Co)(_2)As(_2) [OD] [238, 241]* Ba(Fe,Ni)(_2)As(_2) [297]* Ba(Fe,Co)(_2)As(_2) [UD] [241]*</td>
<td>KFe(_2)As(_2) [4K] [211, 309] BaFe(_2)(As,P)(_2) [OP,31K] [205, 149] (Ba,K)Fe(_2)As(_2) [UD] [242]</td>
</tr>
<tr>
<td>111</td>
<td>LiFeAs [18K] [298, 258]</td>
<td></td>
<td>LiFeP [6K] [299]</td>
</tr>
<tr>
<td>11</td>
<td>Fe(Se,Te) [27K] [231, 246]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
FE BASED SUPERCONDUCTORS

Role of nematicity?

Breaks the tetragonal symmetry.

Related to magnetic fluctuations.

Nematic order postulated for the pseudogap in cuprates.

http://www.ifsc.usp.br/coloquio/2013/Fernades.pdf
FE BASED SUPERCONDUCTORS

Pseudogap


Accompanied by orbital ordering. PRB 89, 045101 (2014)
MAKING CONNECTION BETWEEN CUPRATES AND FE SUPERCONDUCTORS

Spin fluctuations play the role of phonons.

The “normal” state can be described as a nearly AF Fermi liquid (unconventional Fermi liquid close to an AF instability).

Note: calculating the effective interaction is not trivial because vertex corrections can be important (Migdal’s theorem doesn’t apply)
If the magnetic susceptibility has a peak at \( q \) (remember nesting) the interaction is also peaked at \( q \) and positive.

\[
\Gamma_s(k, k') = \frac{3}{2} U^2 \frac{\chi_0(q)}{1 - U \chi_0(q)}
\]

If you look at the interaction in real space

It changes sign with position!!

\( q=(\pi,\pi) \)

Hirshfield et al. 1106.3712

SPIN-FLUCTUATION MECHANISM

Square lattice at half-filling:

At \( q = (\pi, \pi) \) the spin susceptibility is maximal (nesting)

\[
V_{k,k'} = V_{k-k'} = V_q \propto \chi_q > 0 \quad q = (\pi, \pi)
\]

To fulfill the gap equation, you need an anisotropic gap such that

\[
\Delta_k = -\frac{1}{\Omega} \sum_{kk'} V_{kk'} \frac{\Delta_{k'}}{2E_{k'}}
\]

\[
\text{sign}(\Delta_k) = -\text{sign}(V_{k,k'}) \text{sign}(\Delta_{k'})
\]

\[
\Delta_k = \frac{\Delta_0}{2} (\cos k_x - \cos k_y)
\]

\[
\Delta_{k+(\pi, \pi)} = \frac{\Delta_0}{2} (-\cos k_x + \cos k_y) = -\Delta_k
\]

Hirshfield et al.
**SPIN-FLUCTUATION MECHANISM**

For a multi-orbital system (as Fe-superconductors)

For instance, spin fluctuations related to nesting between electron and hole pockets: \( q = (\pi, 0) \)

\[ S \pm \]

This would lead to an \( s_\pm \)

(as the order parameter averages to zero on the Fermi surface, you also get “Coulomb avoidance”)

arXiv:0901.4790
ELECTRON-PHONON

Not discarded! For cuprates: Phys. Rev. Lett. 105, 257001

Maybe coupled to other degrees of freedom?

For Fe-superconductors


Orbital fluctuations induced by electron-phonon. PRL 104, 157001
Different energy scales involved for underdoped cuprates

$T^*$: Phase transition or crossover (no exp. evidence of phase transition)

$T_c < T^*_{\text{pair}} < T^*_{\text{stripe}}$

Carlson et al, Chapter 21

PRB 56, 6120
Different energy scales involved for underdoped cuprates

At $T^*_\text{stripe}$: stripe formation. Stripes are rivers of charge where holes can move (gain kinetic energy in 1dim). In between, AF regions where the carriers are localized.

At $T^*_{\text{pair}}$: local pairing (spin-gap) within the 1DEGs (stripes). Pairs can tunnel to neighboring 1DEG (which in principle has another $k_F$). This way the system gains kinetic energy in a perpendicular direction as well. There is finite $\Delta$ but not fixed phase.

At $T_c$: phase coherence sets in (Josephson coupling between stripes) $\rightarrow$ superconductivity.

$T_c < T^*_{\text{pair}} < T^*_{\text{stripe}}$
**RESONATING VALENCE BONDS**

Mottness from the start.

Pairing scale very large (related to $T^*$)

However, spin liquid not found on cuprates.

The pseudogap phase is in fact a gapped phase (pseudo in experiment due to imperfections or dynamic effects)

Circulating currents, PRB 55, 14554
Charge order PRL 87, 056401
d-density wave PRB 63, 094503
Nematic phase arXiv:1404.0362
Different mechanisms for different materials and for different parts of the phase diagrams?

![Phase diagram](wikimedia)
POST HIGH $T_c$ PRINCIPLES TO FIND SPC
MAZIN, NATURE 464, 183 (2010)

• Layered structures
• Carrier density should not be too high (compared to conventional metals)
• Transition metals of the fourth period (3d) are good
• Magnetism is essential
• Proper Fermi surface geometry is essential (in relation to spin excitations)

Corollary: work with solid state chemists (you need complex chemical compounds)
OUTLINE

• **Superconductivity**
  • Properties (zero resistivity, Meissner effect)
  • Understanding (pairing, BCS, Ginzburg-Landau)
  • Electron-phonon interaction (conventional superconductivity)

• **Unconventional superconductivity (unsolved)**
  • What are the new issues.
  • What are the proposals.