Stay Away from Theorists

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Rules of B. Matthias for discovering new superconductors

1. high symmetry is best
2. peaks in density of states are good
3. stay away from oxygen
4. stay away from magnetism
5. stay away from insulators
6. stay away from theorists

From Steve Girvin’s lecture (Boulder Summer School 2000) courtesy of Matthew Fisher
Everything You Wanted to Know About Pair Formation (But Were Afraid to Ask)

(the electron-phonon case)

1. 1st $e^{-}$ attracts + ions
2. Ions shift position from red to blue
3. 1st $e^{-}$ moves away
4. 2nd $e^{-}$ sees + ion hole and moves to former position of 1st $e^{-}$

Interaction is local in space (s-wave pairs, $L=0$, $S=0$) but retarded in time ($T_c \ll \text{Debye frequency}$)
In conventional electron-phonon theory, we rapidly went from a weak coupling treatment – BCS - to a strong coupling theory – Eliashberg - in just a few years because of the utility of Migdal’s theorem.
Unfortunately, this didn’t help us much!

1. Didn’t predict buckeyballs
2. Didn’t predict MgB$_2$
3. Predictions based on MgB$_2$ (Li$_x$BC, etc.) didn’t pan out
4. Heavy fermion superconductors unexpected
5. Cuprates as well
6. Pnictides too
7. And we can only imagine what’s next …
So, what do we mean by unconventional superconductivity?

1. An order parameter that changes sign as a function of $k$

2. A pairing mechanism different from electron-phonon theory

Examples

- superfluid $^3$He
- heavy fermion superconductors
- organic superconductors
- cuprate superconductors
- iron arsenide superconductors

As pointed out by Hertz, Levin and Beal-Monod (SSC 1976), there is no Migdal theorem for electron-electron theories
Heavy Fermion Superconductors

CeCu$_2$Si$_2$ – Steglich, PRL 1979
UBe$_{13}$ – Bucher, PRB 1975; Ott, PRL 1983
UPt$_3$ – Stewart, PRL 1984
U$_2$PtC$_2$ – Matthias, PNAS 1969

PuCoGa₅ – LANL group – Nature 2002 ($T_c = 18.5$ K !)
Ferromagnetic Superconductors

$\text{UGe}_2$ – Saxena, Nature 2000; $\text{URhGe}$ – Aoki, Nature 2001

Pfleiderer & Huxley, PRL (2002)

Levy et al., Science (2005)
UX$_3$ – most of them AuCu$_3$ cubic structure expect

UPd$_3$ – dHCP (localized f electrons, quadrupole order)

UPt$_3$ – HCP (itinerant f, heavy fermion superconductor)

Koelling et al., PRB (1985)
Organic Superconductors

Ardavan et al., JPSJ (2012)

Kurosaki et al., PRL (2005)
Electronic Structure of Cuprates

- LaO
- CuO$_2$
- LaO

\[ \begin{array}{c}
\text{BiO} \\
\text{BiO} \\
\text{SrO} \\
\text{CuO} \\
\text{CuO} \\
\text{SrO} \\
\text{BiO} \\
\text{BiO} \\
\text{SrO} \\
\text{CuO} \\
\text{CuO} \\
\text{SrO} \\
\text{BiO} \\
\text{BiO} \\
\end{array} \]

- UHB
- LHB

- $\varepsilon_d$
- $\varepsilon_p$

- $\mu$

Anderson Science (2007)
Short tutorial on cuprates

$\text{Cu}^{2+}$

Large $U$ charge-transfer gap $\Delta_{pd} \sim 2 \text{ eV}$

Mott insulator

best evidence for large $U$

antiferromagnet $J \sim 1400 \text{ K}$

$H = -t \sum_{i,j,\sigma} c_{i\sigma}^+ c_{j\sigma} + U \sum_i n_{i\uparrow} n_{i\downarrow}$

Hubbard

$t = 0.3 \text{ eV}, \quad U = 2 \text{ eV}, \quad J = 4t^2/U = 0.12 \text{ eV}$

(design from PWA)
Iridates - spin-orbit plus $d^5$ configuration leads to a half filled band

Cuprates are Mott insulators, have a half filled band, and a large superexchange $J$

So are iridates!

If doped, will they be high $T_c$ superconductors?

Wang & Senthil, PRL (2011)
Phase Diagram of Cuprates

Temperature (Kelvin)

Hole Doping (x)

- Antiferromagnet
- Pseudogap
- Spin glass
- Superconductor
- "Normal" state
- $T_\text{c}$
- $T_\text{N}$
- $T^*$
- $T_{\text{coh}}$ (?)
- Fermi Liquid
- $T_\text{c}$
Cuprates have d-wave pairs
(L=2, S=0)

van Harlingen; Tsuei & Kirtley - Buckley Prize -1998

Artwork by Gerald Zeldin (2000)
Photoemission spectrum above and below $T_c$ at momentum $k = (\pi,0)$ for Bi2212

![Graph showing photoemission spectrum with peaks and dips at different binding energies.]

Incoherent normal state

Coherent superconductor

Norman et al., PRL (1997)
Electronic Phase Diagram Based on Antinodal Spectra

Chatterjee et al., PNAS (2011)
What is the Pseudogap Due to?

1. Spin singlets
2. Pre-formed pairs
3. Spin density wave
4. Charge density wave
5. d density wave
6. Orbital currents
7. Flux phase
8. Stripes/nematic
9. Valence bond solid/glass
10. Combination?
Orbital moments above $T_c$ in the pseudogap phase (Bourges, Greven)

Fauque et al.
PRL (2006)
hole density shows a “4a period bond centered electronic glass” & the pseudogap exhibits a nematic anisotropy

Kohsaka et al., Science (2007)  
Lawler et al., Nature (2010)
Is the Pseudogap a Nematic Phase?

Chang et al., Nat Phys (2012)

RVB Model (Anderson, Lee & Nagaosa, Randeria & Trivedi, etc.)
It postulates a liquid of spin singlets rather than a Neel lattice

Pseudogap phase corresponds to a d-wave pairing of spins (left). At half filling, this is quantum mechanically equivalent to a staggered flux state (middle). The spin gap, $\Delta$, is not equivalent to the superconducting order parameter, $\Delta_{sc}$ (right).
Two Theories of the Cuprate Phase Diagram

**RVB**

- Strange metal
- Spin gap
- Fermi liquid
- Superconductor

**Quantum Critical**

- Quantum critical
- Ordered
- Fermi liquid
- $T_c$

Relation of $T^*$ to $T_c$

- (1)
- (2)
- (3)
What is the origin of pairing?

Is there a pairing glue?

Is it instantaneous?

“We have a mammoth and an elephant in our refrigerator—do we care much if there is also a mouse?”

Antiferromagnetic spin fluctuations can lead to d-wave pairs (an e- with up spin wants its neighbors to have down spins)

Heavy Fermions - Varma (1986), Scalapino (1986)
High T_c - Scalapino (1987), Pines (1991)

(plots from Doug Scalapino)
Cluster DMFT

Weber et al., arXiv (2011)
Pairing occurs below mean field transition temperature
Coherence occurs below phase ordering temperature
Superconductivity occurs only below both temperatures
Composite Systems – A route to high $T_c$

Berg et al., PRB (2008)

Mukuda et al., JPSJ (2012)
Ca$_2$CuBr$_2$O$_2$

K$_2$CoF$_4$

Sr$_4$V$_3$O$_{10}$

Sr$_2$MoO$_4$

Data Mining

Klittenberg & Eriksson, arXiv (2011)
Iron arsenide and chalcogenide superconductors

There are a number of different crystal structures

Tapp et al., PRB (2008)

Rotter et al., PRL (2008)

Hsu et al., PNAS (2008)
ThCr$_2$Si$_2$ crystal structure seems to be ubiquitous
Coexistence of superconductivity & magnetism

Sm-1111


Canfield & Budko, ARCMP (2010)
In a quantum critical scenario, an “ordered” phase exists on one side of the critical point, the corresponding “quantum disordered” phase (Fermi liquid) is on the other side.
Similarity of Phase Diagrams

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

**Heavy Fermions**

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

**Organics**

- **Cu[N(CN)$_2$]Cl**
- **Cu[N(CN)$_2$]Br**
- **Cu(NCS)$_2$**

**Pnictides**

- **Paramagnetic Mott insulator**
- **Critical endpoint**
- **Antiferromagnetic insulator**
- **Unconventional superconductivity**

**Cuprates**

- **Critical endpoint**
- **Paramagnetic metal**
- **Unconventional superconductivity**

**Control parameter, $\delta$**

- **AFM**
- **SC**
- **AFM + SC**

- **NFL**

- **$T_c$**
- **$T_\alpha$**
- **$T_\beta$**

**Temperature, $T$ (K)**

- **140**
- **120**
- **100**
- **80**
- **60**
- **40**
- **20**
- **0**

**x**

- **0.00**
- **0.05**
- **0.10**
- **0.15**
- **0.20**
Even Buckeyballs have a Similar Phase Diagram

\[ \text{Cs}_3\text{C}_{60} \]

Takabayashi et al., Science (2009)
26K superconductivity in layered hafnium nitride

Filling up the Brillouin Zone

Pickett, J Supercond (2006)
Metallic Hydrogen: A High $T_c$ Superconductor?

Ashcroft, PRL (1968)
Super High $T_c$ Superconductivity?

Replace ions by heavy holes (leading to a high effective $\omega_D$)

Abrikosov, JETP Lett. (1978)
Holographic approach to high temperature superconductors?

Sachdev, ARCMP (2012)
Connection to Other Fields
(Cold Atoms, Nuclear Matter, …)
An increased $T_c$ leads to a reduced phase stiffness.
I leave you with some “infamous” Bernd Matthias quotes:

I also want to begin with a friendly introduction because the rest of my talk will not be so friendly – *1969 Spring Superconducting Symposium (NRL, 1969)*

The electron-phonon interaction always reminds me of the man who is looking for his keys under a street light and his friends say “but you didn’t lose them here, you lost your keys over there”. “I know, but it is too dark over there.” – *ditto*

the first symposium on organic superconductors is being held in Hawaii. To my knowledge, this is the first symposium ever to be held on a nonexistent subject. – *Superconductivity, ed. Frank Chilton (North Holland, 1971), p. 69*

the success of the 5f electron superconductivity mechanism in being able to predict even ferromagnetism is in my opinion fairly convincing evidence of the magnetic rather than vibrational interaction – *ditto*

That of course leads you to Green’s functions and the absence of any further predictions. – *Science and Technology of Superconductivity (Plenum, 1973)*

Unless we accept this fact and submit to a dose of reality, honest and not so honest speculations will persist until all that is left in this field will be these scientific opium addicts, dreaming and reading one another’s absurdities in a blue haze. - *Comments Solid State Physics, 3, 93 (1970)*