What’s Up with the Cuprates?

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Electronic Structure of Cuprates

Bi2212

Anderson Science (1987)
The Undoped Phase is a Neel antiferromagnet

Vaknin et al., PRB (1990)
d-wave pairing revealed by phase sensitive tunneling
(Buckley Prize – van Harlingen, Ginsberg, Kirtley, Tsuei – 1998)
(with the experiment suggested by Tony)
d-wave pairs involve electrons on near neighbor copper sites (Buckley Prize – Campuzano, Johnson, Shen – 2011)

\[ \Delta_k = \cos(k_x a) - \cos(k_y a) \]

Incoherent normal state
Coherent superconductor

Ding et al., PRB (1996)
Norman et al., PRL (1997)
Coherent quasiparticles in superconducting and overdoped phases

Kaminski et al., PRL (2003)  
Chatterjee et al., PNAS (2011)
The Strange Metal Phase exhibits linear T resistivity

Martin et al., PRB (1990)
This is reflected in the T and $\omega$ dependences of ARPES linewidths

Valla et al., Science (1999)
As well as that of optics data

Holographic Approach – AdS/CFT

“Planckian” dynamics, $\tau \sim \hbar/2\pi k_B T$

$\text{AdS}_2 \rightarrow \text{CFT}_1$

Zaanen et al., Cambridge (2016)
Near $T^*$ (pseudogap line), anomalies are seen in various properties.
Singlet Formation (NMR, bulk susceptibility)

Curro et al., PRB (1997)
Lee et al., RMP (2006)
"Pre-formed" Pairs (ARPES, Nernst, diamagnetism, optics, etc.)

Norman et al., PRB (2007)

Li et al., PRB (2010)

Dubroka et al., PRL (2011)
Loop Current Order (Varma)

Fauque et al., PRL (2006)
Recent corroborating evidence (SHG, $\mu$SR)

Zhao et al., Nature Physics (2016)

Charge order in vortex “halos” of Bi2212 (STM)

Short range charge order in YBCO (resonant & hard x-rays)

Ghiringhelli et al., Science (2012)  
Chang et al., Nature Physics (2012)
Charge order becomes long ranged in a field (NMR, x-rays)

STM reveals a d-wave form factor for the CDW

Pair Density Wave State in the vortex “halo” (STM)

(see also Wang et al & Dai et al, arXiv)

Edkins et al., arXiv (2018)
Is a biaxial PDW the origin of the small electron pocket seen by dHvA?

Norman & Davis
arXiv (2018)
Origin of Superconductivity

- Doped Mott Insulator
- Doped Spin Liquid
- Spin fluctuations
- Coulomb correlations (Leggett, see talk by van der Marel)
- Role of charge fluctuations and the lattice

Numerical Studies (DMFT, FRG, QMC, DMRG, PEPS, DMET)

Corboz, Rice, Troyer, PRL (2014)
Huang et al., Science (2017)
CuTeO$_4$ - Monoclinic distorted CuO$_2$ square net
CuO$_6$ quasi-octahedral, Cu-O-Cu bond angles $122.5^\circ$ & $126.1^\circ$

CuTeO$_4$ - Falck et al., Acta Cryst. B (1978) grown hydrothermally at 650 C
but Cu$_3$TeO$_6$ more thermodynamically stable

Botana & Norman, PRB (2017)
Herbertsmithite - $\text{ZnCu}_3(\text{OH})_6\text{Cl}_2$ – a Kagome quantum spin liquid

120 degree CuO bonds

Shores et al., JACS (2005)
Lee et al., Nature Materials (2007)
Norman, RMP (2016)
Doping with Li leads to localized carriers – Kelly et al., PRX (2016)
Herbertsmithite has a much larger gap (~3.5 eV) than a cuprate

Cu$_5$V$_2$O$_{10}$(CsCl), averievite, has a Cu kagome layer and Cu-V honeycomb layers separated by CsO$_2$ layers (a pyrochlore slab)

Botana, Zheng, Mitchell, Norman, unpublished
Fluoroargentates (analogues of cuprates?)

Cs$_2$AgF$_4$

KAgF$_3$, K$_2$AgF$_4$, K$_3$Ag$_2$F$_7$

Mazej et al., CrystEngComm (2009)
Quantum Chemical Considerations – Silver Flourides

Grochala & Hoffmann, Angew Chem (2001)
$\textit{R}_4\textit{Ni}_3\textit{O}_8$ obtained from $\textit{R}_4\textit{Ni}_3\textit{O}_{10}$ by hydrogen (topotactic) reduction resulting in the loss of apical oxygens.

Zhang et al., PNAS (2016)
Unlike La438, which is a charge stripe insulator, Pr438 is a metal with Ni \( dx^2-y^2 \) orbitals near \( E_F \).

Zhang et al., Nature Physics (2017)
Botana, Pardo, Norman, PRM (2017)
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)

Kim et al., PRL (2009)
Fermi arcs and d-wave gaps in $\text{Sr}_2\text{IrO}_4$ via K-surface doping

Kim et al., Nature Physics (2016)