The Search for New Superconductors from an Applications Perspective

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Objectives of the Talk

• Looking back – What have we learned about the nature of very high $T_c$ superconductivity in recent decades?

• What does it tell us about the prospects of electric power applications of superconductivity at much higher temperatures?

• Looking ahead – How might we proceed? Or at least provide some guidance
In Search of the Holy Grail

The Quest for a Room Temperature Superconductor

Adapted from a DoE Report
In Nature the Transition Temperature Can Be “Astronomically” High

FIG. 1. (Color online) A schematic outline for the phase diagram of matter at ultrahigh density and temperature. The CFL phase is a superfluid (like cold nuclear matter) and has broken chiral symmetry (like the hadronic phase).
With Some Experimental Evidence

**Superconductor found in neutron star's core**

Science@NASA
Thursday, 24 February 2011

ALABAMA: NASA's Chandra X-ray Observatory has discovered the first direct evidence for a superfluid - a bizarre, friction-free state of matter - at the core of a neutron star.

Superfluids created in laboratories on Earth exhibit remarkable properties, such as the ability to climb upward and escape airtight containers. The finding has important implications for understanding nuclear interactions in matter at the highest known densities.

"The rapid cooling in Cas A's neutron star, seen with Chandra, is the first direct evidence that the cores of these neutron stars are, in fact, made of superfluid and superconducting material," said lead author Peter Shtrernin of the Ioffe Institute in St Petersburg, Russia, of a paper accepted in the *Monthly Notices of the Royal Astronomical Society*.

**Unusual rapid decline in temperature**

Neutron stars contain the densest known matter that is directly observable. One teaspoon of neutron star material weighs six billion tonnes. The pressure in the star's core is so high that most of the charged particles, electrons and protons, merge resulting in a star composed mostly of uncharged particles called neutrons.
But What About a “Room Temperature” Superconductor?

It must:

- Operate in an earthly environment
- Be made from earthly forms of matter
- And from a practical point of view, exhibit good superconducting properties*

* In the past it has been an article of faith that superconducting properties improve as $T_c$ increases
But Higher $T_c$ Does Not Always Bring Higher $J_c$

Thermodynamic Critical Current Density of Various Superconductors

The theoretical maximum current density

Critical Current Density $J_c(0) \times 10^8$ A/cm$^2$

Transition Temperature $T_c$ (K)

$MgB_2$

Conventional Low $T_c$

YBCO

Along ab plane

Along c axis
So What’s Going On?

Factors Governing the Thermodynamic Critical Current Density

For any superconductor:

- **The supercurrent density**
  \[ J_s = n_s e v_s \]

- **The kinetic energy density**
  \[ G_K = \frac{1}{2} n_s m v_s^2 = \frac{1}{2} \frac{m^*}{n_s e^*} J_s^2 = \frac{1}{2} \Lambda_K J_s^2 \]

\[ \Lambda_K = \frac{m^*}{n_s e^*} \frac{4\pi \lambda^2}{c^2} = \text{Kinetic inductivity} \]

Large \( J_c \) requires high \( T_c \) and high pair density

\[ J_c = \frac{1}{\sqrt{2}} n_s e^* \frac{\hbar}{m^* \xi} \propto \frac{n_s^*}{m^* T_c} \]

where \( \xi = \text{size of Cooper pair (} \xi \propto 1/T_c \) \)
And How Good is YBCO for Electric Power Applications?
YBCO is the best cuprate superconductor for electric power applications (least anisotropic)

If there are to be commercial electric power applications of superconductivity above 77K, an entirely new superconductor will be required

We should be looking
A Primer on The Fundamentals of Very High Temperature Superconductivity

• What would the Cooper pairs be like?
• Are there generic (pairing mechanism independent) limits on $T_c$?
• How do these insights square with experience?
Whatever Else, The Cooper Pairs Will Be Very Small

The physics of pairing will be local (i.e., real space pairing)
To Determine $T_c$ There are Two Characteristic Temperatures to Consider

Superconductivity arises when electrons (or holes) form pairs and the quantum phases of these pairs order (lock) to form a coherent macroscopic quantum state with a single phase.

Each process has its own characteristic temperature.
The Actual Superconducting Transition Temperature $T_c$

The Destruction of Superconductivity by Increasing Temperature

Pairs dissociate $T_p$

Phases unlock $T_\phi$

If $T_\phi < T_p \Rightarrow T_c = T_\phi$

If $T_p < T_\phi \Rightarrow T_c = T_p$

(And $T_\phi$ renormalizes down to $T_p$

as in BCS theory)
Thermodynamic Limit to the Transition Temperature
Due to Thermal Phase Fluctuations

Independent of the pairing interaction, phase ordering is lost when the RMS phase difference $\Delta \phi$ across a Cooper pair due thermal phase fluctuations is of order $\pi$

$$V_p = \text{Volume of a Cooper pair}$$

Temperature at which thermal fluctuations produce phase unlocking

Energy to twist phase by $\pi$

$$\frac{1}{2} \frac{1}{\Lambda_K} (\nabla \phi)^2 V_p = k_B T_\phi$$

$$1/\Lambda_K = \text{Phase stiffness}$$

$$T_\phi \approx \frac{1}{2} \frac{1}{\Lambda_K} \frac{\xi_{ab}}{\gamma} = \left( \frac{\hbar^2 n_s * \xi_{ab}}{2 m^* \gamma} \right) \propto \frac{n_s * 1}{m^* \gamma T_p}$$

$\gamma = (M/m)^{1/2} \text{ GL mass anisotropy}$
Is a Room Temperature Superconductor Possible?

Notional High Temperature Superconductors Relative to YBCO ($v_F$ constant)

<table>
<thead>
<tr>
<th>$T_p$</th>
<th>$T_c$</th>
<th>$\frac{J_c}{J_{c,YBCO}}$</th>
<th>$\gamma \rightarrow 1$</th>
<th>$n_s^* \times 2$</th>
<th>$n_s^* \times 10$</th>
</tr>
</thead>
<tbody>
<tr>
<td>90 K</td>
<td>90 K</td>
<td>1</td>
<td>90 K</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>180 K</td>
<td>72 K</td>
<td>2</td>
<td>180 K</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>270 K</td>
<td>54 K</td>
<td>3</td>
<td>270 K</td>
<td>6</td>
<td>30</td>
</tr>
<tr>
<td>360 K</td>
<td>36 K</td>
<td>4</td>
<td>180 K</td>
<td>8</td>
<td>40</td>
</tr>
</tbody>
</table>

Yes, but will require strong interactions, high pair density and low anisotropy
General Considerations vs Experience Relevant for the Search for a Room Temperature Superconductor

**Commonly Stated Empirical Guidance***

- Increase interactions
- Low carrier density
- Two dimensional

**General Physical Considerations**

- Increase interactions
- High carrier density
- Three dimensional

There is an apparent conflict here

*Based on the cuprate superconductors*

* In addition, very small pair size $\rightarrow$ Local pairing on near atomic level $\rightarrow$ Must learn to think and calculate in real space more like the chemists do
Fundamental Questions

The general physical considerations presented above are derived from thermodynamic reasoning and therefore carry great power. This clearly raises some very fundamental questions:

• Can strong interactions and high pair density be achieved at the same time? Or are they incompatible? (If the electron density is very high, one may just get a simple metal with weak interactions)

• Is reduced dimensionality beneficial (or possibly necessary) for high $T_c$? For example, to weaken an anti-ferromagnetic parent phase through increased fluctuations to allow superconductivity to emerge upon doping
Now Let’s Focus on the Possible Specific Interactions Seemingly Favorable for Very High Temperature Superconductors

• *What do we know empirically?*

• *What can we say theoretically?*

• *What guidance do theory and experiment provide us?*
So What Can We Learn From the Present High $T_c$ Superconductors?

![Graph showing the temperature and year for various superconductors, including Pr(O-F)FeAs.](image-url)
# Empirical Guidance on Specific Interactions

<table>
<thead>
<tr>
<th>Material Archetype</th>
<th>$T_c$</th>
<th>Interaction</th>
<th>Guidance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bismuthates (i.e., doped BaBiO$_3$)</td>
<td>30K</td>
<td>Charge + Lattice</td>
<td>Doped Negative $U$ Insulator</td>
</tr>
<tr>
<td>Cs$<em>3$C$</em>{60}$</td>
<td>40K</td>
<td>Lattice + Correlation (charge)</td>
<td>El-Ph Covalent Bonds</td>
</tr>
<tr>
<td>MgB$_2$</td>
<td>40K</td>
<td>Lattice</td>
<td>El-Ph Covalent Bonds Prediction</td>
</tr>
<tr>
<td>Fe-Based</td>
<td>50K</td>
<td>Spin</td>
<td>Antiferromagnetism Multiple orbitals</td>
</tr>
<tr>
<td>Cuprates</td>
<td>130K</td>
<td>Spin</td>
<td>Doped Antiferromagnetic Positive $U$ Mott Insulator</td>
</tr>
<tr>
<td>Trace High $T_c$ Anomalies</td>
<td>$&gt;\text{Room Temperature}$</td>
<td>?</td>
<td>Shouldn’t Ignore</td>
</tr>
</tbody>
</table>

Electronic (charge and spin) interactions look good
A Case Study – The Bismuthates
Superconductivity in a doped charge-ordered oxide insulator
Crystal Structure of BaBiO$_3$

*Distorted Perovskite*

Note three dimensional structure
Charge-Disproportionated (Negative U) Superconductors (e.g., BaBiO$_3$)

*A Failure of LDA Theory → A new class of correlated insulator*

2 $Bi^{4+}(4s^1) → Bi^{3+}(4s^2) + Bi^{5+}(4s^0)$

*Oxygen atoms move to screen charge (Breathing mode)*

Superconductivity arises upon doping (Ba$_{1-x}$K$_x$BO$_3$ and BaPb$_{1-x}$Bi$_x$O$_3$)
Phase Diagrams of the Superconducting Bismuthates

Note similarity to the phase diagrams of the cuprate superconductors but where the ordered insulating state is in the charge sector.
Optical Properties -- Puchkov et al

- Only $3 \times 10^{20}$ carriers in Drude Peak and little change with $x$.
- Strong MIR peak

**FIG. 1.** The optical conductivity of $\text{Ba}_{1-x}\text{K}_x\text{BiO}_3$ just below and just above the insulator-metal transition. The characteristic energies $\hbar \omega_\text{max}$ and $\hbar \omega_\text{0}$, used in the text, are shown. The inset: the lines represent the real part of the optical conductivity obtained from the KK analysis of reflectivity spectra. The symbols show results of ellipsometric measurements.

**FIG. 4.** The optical conductivity of the three metallic samples BKBO in the superconducting and the normal states. The results of magnetization measurements are shown on the insets. The scattering rate values $1/\tau$ in the normal state are shown on the frequency axis for all three samples. The shaded squares represent the spectral weight of the superconducting carriers. The London penetration depth $\lambda_\text{L}$ is inversely proportional to the side of the square. The position of the superconducting gap energy $2\Delta_\text{L}$ is shown by the arrows.
Max $T_c$ occurs at crossover between weak and strong coupling – Seems to be a generic feature of strong interactions (including the el-ph interaction)
A New Theoretical Concept

High $T_c$ and High Pair Density Superconductor Using a Normal Metal/Negative-U Insulator Proximity Effect

Electrons coherently hop on and off the pairing centers to induce superconductivity in the normal metal

A key element here is the role of two distinct sets of electrons that are separated in space

$T_c \text{ max } \approx 0.08 U$

FIG. 1. (Color online) $T_c (\square)$ and $T_{MF} (\bigcirc)$ obtained from solving Eqs. (6)–(9) numerically for $n=1.5, t=1, U=1$ as a function of $t_\perp$. The dashed curves are fits to the data according to Eqs. (13) and (15). $A=0.235$ was used in the fit.

So Where Do We Stand in our Quest for a Useful Room Temperature Superconductor?

- There are generic limits to $T_c$
- But they do not preclude a room temperature superconductor, if the anisotropy is low and the carrier density high
- The challenge will be to achieve strong interactions under these conditions; there are some new ideas how to do this
- And we must learn how to deal with very small Cooper pairs
- The conditions necessary for room temperature superconductivity are consistent with those needed for good practical performance
Wish Good Luck to Those Willing to Try
(and those that fund them)