High-Temperature Superconductivity: From History to Mystery

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Outline

I. Lessons Learned
   But, We Still Care About Fundamentals
II. Some History to Define:
   Conventional vs. Unconventional SCs
III. Ubiquitous Phase Diagram and
   “Electron Matter” in Unconventional
IV. Point-Contact Spectroscopy (PCS)
V. Towards Predictive Design...
VI. Conclusion: Experiment / theory progress!
   And we are having fun!
Lessons Learned: Kamerlingh Onnes & ASC

1909  Liquefied Helium
1911  Discovered Superconductivity: \( T_c \) and later \( I_c \)
1913  Received Nobel Prize
1913  \textit{Press Releases on possible applications}
1926  Paper on Critical Field (\( H_c \))
Lessons Learned, Continued

1930s and following: Much ASC Research & Applications

1957  **BCS THEORY (after applications realized)**

1979  First Unconventional SC Identified

1986  HTS Discovered (Bednorz and Müller)

1987  HTS Nobel Prize for Discovery

1989  R&D in HTS Cables

1991  Successful HTS Cables Demoed

2016  ASC 2016: Plethora of amazing applications rept.

2016  **Mechanisms & Predictive Design: A Mystery!**

So why give a CARE about fundamentals?
Lessons Learned: So Why Care?

Reason we put on proposals, some consider a “belief” but really making progress towards this goal:

“Understanding the mechanisms of unconventional SC will lead to predictive design of new SCs that may have transformative applications.”

Another reason; just as important:

The physics is absolutely gorgeous!

...and, it’s nice to know what your siblings are up to...

Few motivational slides follow...

Warning: Extreme analogies!
Recent Inspiration: Gravity
Gravity

Condensed Matter

DoS

Kip Thorne, Kavli Lecture

Newton

Fermi

Einstein

BCS

Dark Energy

Electron Matter
What is Electron Matter?

What it is not:

• Fermi Liquid or Superconductor

General definitions:

• **Theory**: The normal-state electronic properties cannot be explained by the crystal structure

• **Experiment**: The electrons assemble into astounding states: Like form clumps, line up, or get really heavy.
# Lessons Learned: Why We Care

## Two Great Unsolved Problems Today in Physics

<table>
<thead>
<tr>
<th>PROGRESS</th>
<th>Gravity</th>
<th>Condensed Matter</th>
<th>PROGRESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forces between objects derived from mass and positions</td>
<td>Newtonian -Classical</td>
<td>Fermi Liquid -simple metals</td>
<td>Properties derived from crystal atoms and positions</td>
</tr>
<tr>
<td>Distortions in background (space-time continuum)</td>
<td>Einsteinian -General Relativity</td>
<td>BCS SC -One Electron Matter solved!</td>
<td>Distortions in background (lattice via el-phonon int.)</td>
</tr>
<tr>
<td><strong>UNSOLVED:</strong> May show how stars form...etc.</td>
<td>Dark Energy and Dark Matter</td>
<td>Electron Matter (correlations)</td>
<td><strong>UNSOLVED:</strong> All unconv SCs have them</td>
</tr>
</tbody>
</table>
History: 2006 DoE-BES Report: “$T_c$ vs. Time” & Phase Diagram

- HgBaCaCuO @ 30 GPa: record $T_c$ at 164 K
- TIBaCaCuO
- BiSrCaCuO
- HgTIBaCaCuO
- HgBaCaCuO
- YBaCuO
- MgB$_2$
- LaBaCuO
- RbCsC$_{60}$ @ 1.4 GPa
- Cs$_3$C$_{60}$
- K$_3$C$_{60}$
- Li @ 33 GPa
- PuCoGa$_5$
- Li$_2$Cu$_2$Si$_2$
- CeCu$_2$Si$_2$
- UBe$_{13}$
- UPd$_2$Al$_3$
- CeCoIn$_5$
- CNT
- CNT
- CNT
- CNT
- CaC$_6$
- YbC$_6$
- d-SC
- fl-SC
- NFL
- AFI
- CO
- M
- $T^*$
- $T_N$
- SG

S-wave metallic SC

Plenary presentation 4PL-03 given at ASC 2016; Denver, Colorado, USA, September 4 – 9, 2016.
History – Discovery

1911 Heike Kamerlingh Onnes

1908: Liquefied He
1911: Curiosity led to measuring the resistance of Hg mercury, expecting:

1913: Nobel Prize! And stated “superconductors world impact the world energy crisis!”
History – Matthias Era

Next few decades, Tc slowly increased through systematic tests of elements, alloys, and compounds.

1952: Bernd Matthias discovered first “new class” of superconductors, combining ferromagnetic and semiconducting elements: \( \text{CoSi}_2 \)

Matthias’ Rules:
1. Transition metals are better than simple metals
2. Peaks of density of states at Fermi level good
3. High symmetry is good: Cubic best
4. Stay away from oxygen, magnetism, insulating phases, and theorists.

- Geballe and Hulm, “Bernd Theodore Matthias” – NAS ‘96
- W. E. Pickett, “The other HTS” ‘01
History – High Critical Current, \( J_c \)

Also in 1952, John Hulm & George Hardy discovered the first of the “A15” superconductors.

\[ A_3B \text{ structure, with } A = \text{transition metal} \]

Bernd Matthias then discovered over 30 A15s with values of \( T_c \) ranging up to 23 K for \( \text{Nb}_3\text{Ge} \).

These were the first superconductors to show a high critical current in a strong magnetic field: Crucial for applications!
History – Practical Wires

1963 – Hulm (Westinghouse) made the first practical wires of **Nb:Ti** (mat’l discovered at Rutherford-Appleton Labs, UK)

- Random alloy with a high-$T_c$ and high $J_c$
- Not as high as A15s – but malleable and reliable
- Industry standard for applications (unless NEED high $J_c$)

“High $T_c$ gets Nobel prizes, High $J_c$ saves lives”

-- John Rowell
History – Tunable and Novel

1979: Frank Steglich: superconductivity in heavy fermion materials *that have*
- A magnetic ground state
- Electron masses: up to 1000 x $m_e$

Led to discovery of the “domed” phase diagram

1st “unconventional” SC: Magnetism *good* for SC
*(BCS el-ph mech. breaking down)*
History – Oxides to Cuprates

1964: Marvin Cohen **predicts** SrTiO₃
1983: Mattheiss and Hamann **predict** BaₖₓBi₁₋ₓO

1986: Bednorz and Muller: Laₙ₋ₓBaₓCuO₄

1987: Wu ... Chu: YBa₂Cu₃O₇; Tc = 90 K
History – From the Copper to the Iron Age of HTS (2008)

Hosono (Japan): $\text{LaFeAsO}_{1-x}\text{F}_x$, $T_c = 26$ K
Zhao (China): $T_c = 58$ K

A second class of high-temperature superconductors had finally been found: Is there a third?
History – Hydrogen Sulfide at 203 K

2015: Mikhail Eremets
Looks like a conv. SC at ~ 150 GPa

1. Doesn’t look too practical
2. Conventional: BCS el-phonon
   (No electron matter)

Just too cool not to mention here!
Recap: What is Electron Matter?

What it is not:

• Fermi Liquid or Superconductor

General definitions:

• **Theory**: The normal-state electronic properties cannot be explained by the crystal structure

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Conventional Superconductors

\( T_c \leq 40 \text{ K} \) (except \( H_2S \); \( T_c \sim 202 \text{ K} \))

Above \( T_c \): Simple metal
\( (\text{Fermi Liquid}) \)

Below \( T_c \): Cooper pairs: \( (\text{Electron-Phonon Mediated BCS; BdG eqns.}) \)
Conventional Superconductors

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Unconventional Superconductors

$T_c \leq 165 \, K$

Ubiquitous “Domed” phase diagram

Above $T_c$:

FAR RIGHT side of phase diag:
Simple metal ($Fermi\, Liquid$)

Below $T_c$:

Cooper pairs: ($Electron-Phonon\, Mediated\, BCS;\, BdG\, eqns.$)

Above $T_c$:

Rest of phase diag: Electron Matter ($Non-Fermi\, Liquid;\, correlated$)
Unconventional Superconductors

\( T_c \leq 165 \text{ K} \)

Ubiquitous “Domed” phase diagram

Above \( T_c \): FAR RIGHT side of phase diag:
Simons metal \((\text{Fermi Liquid})\)

Below \( T_c \): Cooper pairs: \((\text{Electron-Phonon Mediated BCS; BdG eqns.})\)

Above \( T_c \): Rest of phase diag: Electron Matter
\((\text{Non-Fermi Liquid; correlated})\)
Ubiquitous Phase diagram: T vs. pressure, doping (more than 50 families)

Heavy Fermions

Cuprates

Fe-Based

Organics

Di-chalcogenides

Electron Matter
Intriguing Point About HTS Dome

1. All Practical High-Tc SCs are Unconventional
2. All Unconventional SCs have Electron Matter
3. Electron Matter Suppresses Tc
4. But you don’t get HTS without it

Must be some kind of delicate balance!

So I study electron matter...
Electron Matter Exists UNDER THE DOME

MagLab fields (45T) suppress the SC to see this. Higher B needed to find nature of N-state under dome*


*You need the HTS cuprates

Why does HTS emerge out of these competing phases?
Some Examples of Electron Matter

- **Electronic Nematicity**
  - Stripes and other “charge clumping”
  - Pseudogap
  - Heavy electrons
  - Quantum criticality
  - And more...

Electron sausage clouds in a square lattice
Some Examples of Electron Matter

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- And more…

**MANY new techniques have been developed to elucidate electron matter, including:**
- **STM**
- **ARPES**
- **RIXS**
- Quantum Oscillations
- Ultra-sensitive transport, thermo, and optical meas.
- **Terahertz**
- **DNP**
- **ICR**

...
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- ICR
- Wish I could discuss them all, but now I’ll outline one of my techniques…
Point Contact Spectroscopy

**Metallic** contact: Junction size < el mean free path

WK Park *et al.*, RSI ‘06
Narasiwodeyar *et al.*, RSI ’15
Tortello *et al.*, RSI ‘16
The Iron Based HTS: $\text{Ba(Fe}_{1-x}\text{Co}_x)\text{As}_2$
PCS on Parent Compound: $\text{BaFe}_2\text{As}_2$

Increasing $T$

$T_{\text{onset}}$ 177 K

$12 \text{ K}$

$T_N \& T_{\text{SPT}}$

20 %

Raw Data
Summary of PCS on $\text{Ba(Fe}_{1-x}\text{Co}_x\text{)}_2\text{As}_2$
Nematic region in $\text{Ba(Fe}_{1-x}\text{Co}_x\text{)}_2\text{As}_2$ Phase Diagram

![Phase Diagram](image)

Arham et al., PRB ‘12
Theory of Point Contact Spectroscopy in Correlated Materials

Wei-Cheng Lee*, Wan Kyu Park*, Hamood Z. Arham*, Laura H. Greene*, and Philip W. Phillips

PNAS (2015)

Shows how PCS specifically filters for Electron Matter!

Wei-Cheng Lee
Notes on Predictive Design of SCs

Matthias’ rules for conventional SC.
1. Transition metals are better than simple metals
2. Peaks of density of states at Fermi level good
3. High symmetry is good: Cubic best
4. Stay away from Oxygen, magnetism, and insulating phases (and theorists!)

Our rules for unconventional SCs
1. Reduced Dimensionality
2. Transition metal & other large U ions
3. Light atoms
4. Charged and multivalent ions
5. Low dielectric constant
6. SC borders antiferromagnetism

Only give materials properties that correlate with increased Tc within a class, but do not help to design new superconductors; and fail to predict new classes

PCS finds electron matter!
No one can predictively design Superconductors: (we are trying...) 

Taming serendipity

The discovery of high-temperature iron-based superconductors in 2008 thrilled researchers because it indicated that there could be another – more useful – class of superconductors just waiting to be found. Laura H Greene shares that enthusiasm and calls for global collaboration to reveal these new materials.
Our Center for Emergent Superconductivity Plans for New Superconductor Design (MGI):

1. Identify Chemical Motifs
   - Reduced dimensionality
   - Symmetry (e.g. tetragonal)

2. Identify Structure Type
   - 1668 known Tetragonal ST.

3. Evaluate Predicted Correlations
   - Lead to superconductivity?

4. Synthesis and measurement
   - Determine crystal structure
   - Measure correlations
   - PCS here

5. Analyze properties
   - Superconducting?
   - Feedback to computation

- Computational electronic structure
  - Density Functional Theory
    - Stable structure and classify
  - First principles Quantum Monte Carlo
    - Exact ground state wave function
  - Dynamical Mean Field Theory
    - Bootstrap using QMC
    - Correlation functions

Feedback to Themes II and III
Conclusions - Future Directions

• Lessons Learned: Great strides in SC accomplished w/o needing microscopic mechanisms

• We still continue to search for fundamentals as the questions themselves are inspiring and beautiful, and it is becoming clear that deciphering the electron matter will help us work out the mechanisms of HTS and lead to predictive design new superconductors.

• New experimental and theoretical techniques offer innovative probes – and great strides have been made!

Are these techniques condensed matter’s LIGO for gravity waves?
Conclusions - Future Directions

- Applications will keep on making progress
- The fundamental questions drive and progress our understanding of these fascinating, materials.
- I see us all working together in the near future

And having fun!