Rubber, Quarks and high-temperature superconductivity: Physics at Strong Coupling
Exotic insulating states of matter
January 14-16th, 2010
The Johns Hopkins University

The workshop will focus on experimental and theoretical developments in the areas of:

• Topological insulators and the stability of their edge and surface states
• Bose insulating states and the 2D superconductor-insulator quantum phase transition
• Mott insulators and underdoped high temperature superconductors
• Other unconventional insulating and related states of matter

Confirmed Speakers:
- Boris Altshuler (Columbia)
- Y. Ando (Osaka)
- Leon Balents (UC Santa Barbara)
- Andrei Bernevig (Princeton)
- Anton Burkov (Waterloo)
- Moses Chan (Penn State)
- Yu Lin Chen (Stanford)
- S. Das Sarma (UMD-College Park)
- Brian de Marco (UIUC)
- Matthew Fisher (Caltech)
- Michael Fuhrer (UMD-College Park)
- Liang Fu (Harvard)
- Allen Goldman (Univ. of Minn.)
- Zahid Hasan (Princeton)
- Charlie Kane (Univ. of Pennsylvania)
- Frank Kruger (UIUC)
- Gene Mele (Univ. of Pennsylvania)
- Joel Moore (UC Berkeley)
- Phuan Ong (Princeton)
- Joe Orenstein (UC Berkeley)
- Iluliana Radu (Katholieke Universiteit)
- Gil Refael (Caltech)
- Benjamin Sacepe (Univ. Geneva)
- Subir Sachdev (Harvard)
- G. Sambandamurthy (SUNY-Buffalo)
- Ian Spielman (NIST)
- Tudor Stanescu (Univ. of W. Virginia)
- Zlatko Tesanovic (Johns Hopkins)
- John Traquada (Brookhaven)
- Jean-Marc Triscone (Univ. Geneva)
- Nandini Trivedi (Ohio State)
- Jim Valles (Brown)
- Ashvin Vishwanath (UC Berkeley)
- Congjun Wu (UCSD)
- Ali Yazdani (Princeton)
- Cenke Xu (Harvard)
- Jongsoo Yoon (Univ. of Virginia)
- Shoucheng Zhang (Stanford)

For further information, please visit:
http://icamconferences.org/jhu2010/
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What is an insulator?
What is an insulator?
What is an insulator?
What is an insulator?

no current flows in an insulator
Temperature

Brightness

Temperature vs. Brightness

Diagram showing the relationship between temperature and brightness, with a circuit illustrating the connection.
Temperature vs. Conductivity

As the temperature increases, the conductivity of the material increases as well.
Why?
Why?

internal structure of electrons
Why?

internal structure of electrons
Why?

Internal structure of electrons

N S

e−

spin
Why?

**internal structure of electrons**

1943 Nobel Prize: O. Stern and W. Gerlach
electron spin=acrobatics
electron spin=acrobatics
electron spin=acrobatics
electron spin=acrobatics
electron spin=acrobatics
electron spin = acrobatics

NO EMPTY STATES

INSULATOR
simple lesson

EMPTY STATES = METAL

ALL STATES FILLED = BAND INSULATOR

band theory of metals
acrobatics = chemistry

<table>
<thead>
<tr>
<th>Element</th>
<th>Atomic Number</th>
<th>Atomic Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na</td>
<td>11</td>
<td>22.98976</td>
</tr>
<tr>
<td>Mg</td>
<td>12</td>
<td>24.305</td>
</tr>
</tbody>
</table>

metals

<table>
<thead>
<tr>
<th>Element</th>
<th>Atomic Number</th>
<th>Atomic Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>19</td>
<td>38.966</td>
</tr>
<tr>
<td>Ca</td>
<td>20</td>
<td>40.0784</td>
</tr>
<tr>
<td>Sc</td>
<td>21</td>
<td>44.955910</td>
</tr>
<tr>
<td>Ti</td>
<td>22</td>
<td>47.867</td>
</tr>
<tr>
<td>V</td>
<td>23</td>
<td>50.9415</td>
</tr>
<tr>
<td>Cr</td>
<td>24</td>
<td>52.000</td>
</tr>
<tr>
<td>Mn</td>
<td>25</td>
<td>54.93804</td>
</tr>
<tr>
<td>Fe</td>
<td>26</td>
<td>55.845</td>
</tr>
<tr>
<td>Co</td>
<td>27</td>
<td>58.93321</td>
</tr>
<tr>
<td>Ni</td>
<td>28</td>
<td>58.69337</td>
</tr>
<tr>
<td>Cu</td>
<td>29</td>
<td>63.546</td>
</tr>
<tr>
<td>Zn</td>
<td>30</td>
<td>65.38</td>
</tr>
</tbody>
</table>

The periodic table of elements is shown with the periodic elements arranged in order of increasing atomic number. The elements are divided into categories such as metals and non-metals.
The image contains a periodic table of the elements, with the elements for acrobatics and metals highlighted. The text reads: "acrobatics = chemistry" in red, and "metals" in blue. The periodic table includes the symbol and atomic number for each element, along with the element name and some additional details.
acrobatics = chemistry

metals
conductivity =
conductivity
conductivity = \frac{1}{\text{resistivity}}
conductivity = 1/resistivity
conductivity = 1 / resistivity
\[ T^2 \]
What is low temperature?
What is low temperature?

Amontons’s Law
What is low temperature?

Amontons’s Law
What is low temperature?

Amontons's Law

\[ P \propto T \]
What is low temperature?

Amontons's Law

\[ P \propto T \]

Absolute zero (\(-270^\circ C\))
What is low temperature?

Amontons's Law

\[ P \propto T \]

Kelvin Temperature Scale

0 K

298 K (room temperature)
'Minds are like parachutes they only function when they are open'- James Dewar, Scottish physicist 1842 –1923 liquified hydrogen, 1898 (20.52K)
'Minds are like parachutes they only function when they are open' - James Dewar, Scottish physicist 1842 – 1923. Liquified hydrogen, 1898 (20.52K)
'Minds are like parachutes they only function when they are open'- James Dewar, Scottish physicist 1842 –1923
liquified hydrogen, 1898 (20.52K)

H. K. Onnes
1898: building lab
Race to zero

'Minds are like parachutes they only function when they are open' - James Dewar, Scottish physicist 1842 – 1923

H. K. Onnes
1898: building lab
1908: liquified Helium (0.9K)

1898: liquified hydrogen, 1898 (20.52K)
H. K. Onnes

1898: building lab
1908: liquified Helium (0.9K)
H. K. Onnes
1898: building lab
1908: liquified Helium (0.9K)

Race to zero

Kelvin

Drude/Lorentz

theory??
Race to zero

H. K. Onnes

1898: building lab

1908: liquified Helium (0.9K)
Race to zero

H. K. Onnes
1898: building lab
1908: liquified Helium (0.9K)
superconductivity

zero resistance: conduction without loss

repulsion of magnetic fields

$79 \text{ B economic loss (US)}$

why?
superconductivity

zero resistance: conduction without loss

$79 \text{ B}
$ economic loss (US)

repulsion of magnetic fields

why?
Coulomb’s Law
Coulomb’s Law
Coulomb’s Law

long-range
Coulomb’s Law

massless particle: photon

long-range
Superconductor

magnet

magnetic field is short-ranged
Superconductor

Magnet

Magnetic field is short-ranged

Photon is massive in a superconductor
$e^{-} + \text{photons}$
 photon is massive
A photon is massive.
photon is massive
A photon is massive.

New carriers of charge generate new carriers of charge.

Photon is massive.

2e−
photon is massive

new carriers of charge

2e^-

\[ e^- + \text{photons} \]
A photon is massive.new carriers of charge

$2e^-$

$e^- + \text{photons}$

$\gamma + \text{photons}$

photon is massive

new carriers of charge
A photon is massive.
electrons are free
electrons are free

Mercury

e-repulsion
electrons are free

e-repulsion
electrons are free

e-repulsion

Standard theory of metals
electrons are free

e-repulsion

Standard theory of metals
electrons are free

1. massive photon
2. zero resistance
3. energy to pull electrons apart (gap)

Standard theory of metals

e-repulsion

Mercury

Hg

80

200.59
electrons are free

1. massive photon
2. zero resistance
3. energy to pull electrons apart (gap)

BCS theory: 1957
Nobel: 1972

Standard theory of metals
electrons are free

Standard theory of metals

1. massive photon
2. zero resistance
3. energy to pull electrons apart (gap)

BCS theory: 1957
Nobel: 1972
Key to BCS

they knew what to look for: weakly interacting objects
Key to BCS

free electrons

high T

they knew what to look for: weakly interacting objects
Key to BCS

free electrons

high $T$

they knew what to look for: weakly interacting objects

L. D. Landau
Nobel: 1962
Key to BCS

free electrons

attraction → 2e

they knew what to look for: weakly interacting objects

high T

low T

attraction → 2e

L. D. Landau
Nobel: 1962
New Superconductors
New Superconductors

Unusually

Good Metal
Matthias Rules for Superconductivity
Matthias Rules for Superconductivity

1.) symmetric lattices
2.) avoid oxygen
3.) avoid magnetism
4.) avoid insulators
Matthias Rules for Superconductivity

1.) symmetric lattices
2.) avoid oxygen
3.) avoid magnetism
4.) avoid insulators
5.) don’t talk to theorists!!
orthorhombic
not cubic

$Y \text{Ba}_2\text{Cu}_3\text{O}_7$

Cuprate Superconductors

ceramics
Nitrogen liquifies at 77K.

Cuprates:
- HgBa$_2$Ca$_2$Cu$_3$O$_8$
- Hg$_{0.8}$Tl$_{0.2}$Ba$_2$Ca$_2$Cu$_3$O$_{8+x}$
- TlCaBaCuO
- Hg$_0$.8 Tl$_0$.2 Ba$_2$ Ca$_2$ Cu$_3$ O$_{8+x}$
- Fe$^-$ based

Timeline:
- 1910: Hg
- 1932: Ni
- 1943: NbN
- 1954: $V_3Si$
- 1976: $Nb_3Ge$
- 1987: YBCO
- 2010: Fe$^-$ based
$100K/machine per year

$77K$ Nitrogen liquifies

$HgBa_2Ca_2Cu_3O_8+x$

$TlCaBaCuO$

$YBCO$

$Hg_0.8Tl_{0.2}Ba_2Ca_2Cu_3O_8+x$

$V_3Si$

$Nb_3Ge$

$YBCO$

$Fe$ – based

$Hg$ 1910
$Ni$ 1932
$NbN$ 1943
$V_3Si$ 1954
$Nb_3Ge$ 1976
$TlCaBaCuO$ 1987
$HgBa_2Ca_2Cu_3O_8+x$ 2010

Nitrogen liquifies at $77K$.
Temperature (K)

Year

1910  Hg
1932  Ni
1943  NbN
1954  $V_3Si$
1976  $Nb_3Ge$
1987  $HgBa_2Ca_2Cu_3O_8+x$
2010  cuprates

Nitrogen liquifies: 77K

$YBCO$

$Fe^−$ based
What is left of Matthias' Rules?

1.) cubic structures
2.) avoid oxygen
3.) avoid magnetism
4.) avoid insulators
What is left of Matthias’ Rules?

2.) avoid oxygen
3.) avoid magnetism
4.) avoid insulators
What is left of Matthias’ Rules?

3.) avoid magnetism

4.) avoid insulators
What is left of Matthias’ Rules?

4.) avoid insulators
What is left of Matthias' Rules?
New Problem: Mottness
Sir Neville Mott
Nobel Prize, 1977

Mott
Insulators
What is a Mott Insulator?

NiO insulates?
What is a Mott Insulator?

NiO insulates?

EMPTY STATES = METAL
What is a Mott Insulator?

NiO insulates?

EMPTY STATES = METAL

band theory fails!
What is a Mott Insulator?

NiO insulates?

perhaps this costs energy

EMPTY STATES = METAL

band theory fails!
Mott Problem: NiO (Band theory failure)

Collonade (N rooms N occupants)

\[ U \gg t \]
classical picture

is forbidden
Are the cuprates in the Mott regime?
Y \text{ Ba}_{2}\text{ Cu}_{3}\text{ O}_{7}

Cuprate Superconductors
interactions dominate: Strong Coupling Physics

\[ \frac{U}{t} = 10 \gg 1 \]
Yes
What is left of BCS?

Free electrons

They knew what to look for: weakly interacting objects

High T

Attraction → $2e^-$

Low T

L. D. Landau
Nobel: 1962
What is left of BCS?

attraction $\rightarrow 2e^-$

they knew what to look for: weakly interacting objects

low $T$
What is left of BCS?

They knew what to look for: weakly interacting objects.
pairing idea:
but what to pair up?
Doping a Mott insulator

$x = \text{fraction of empty rooms (holes)}$
Doping a Mott insulator

\( x = \text{fraction of empty rooms (holes)} \)
Doping a Mott insulator

x = fraction of empty rooms (holes)
Doping a Mott insulator

$x = \text{fraction of empty rooms (holes)}$
Doping a Mott insulator

\[ x = \text{fraction of empty rooms (holes)} \]

\[ X = \frac{3}{16} \]
Mott insulator

$\rho \sim a T$

$\rho \sim a T$

$T$
How does the standard theory of metals breakdown?

$\rho \sim aT$

$6,000,000$ question?
Cuprates: The Perfect Storm

Landau Theory
Band Theory
BCS
collective failure
collective failure

New Concept
"I'm not into this detail stuff. I'm more concepty."
strong coupling: bound states not in high-energy theory
strong coupling: bound states not in high-energy theory
strong coupling: bound states not in high-energy theory

how?
strong coupling: bound states not in high-energy theory

how?

vulcanization
strong coupling: bound states not in high-energy theory

how?

vulcanization

emergent low-energy physics
Quantum Chromodynamics: Protons, neutrons, pions (hadrons)
Quantum Chromodynamics: Protons, neutrons, pions (hadrons)

free quarks and gluons
Quantum Chromodynamics: Protons, neutrons, pions (hadrons)

free quarks and gluons
Quantum Chromodynamics: Protons, neutrons, pions (hadrons)

free quarks and gluons

bound states

Proton

Neutron

\( \pi^0 \)
weakly interacting
what are the new bound states?
Is string theory the answer?
No?
holography
holography

quantum holography

quantum gravity

quantum ⇔ gravity
holography

quantum holography

quantum gravity

$\rho \propto T$
classical vs quantum Mottness

---

is forbidden
classical vs quantum Mottness

is forbidden
classical vs quantum Mottness
Why does a Mott insulator insulate?
is the empty site mobile??
is the empty site mobile??

if yes, then 1.) Mott insulator is a metal, 2.) no magnetic order

New bound state
is the empty site mobile??

if yes, then 1.) Mott insulator is a metal, 2.) no magnetic order

New bound state
doped Mott insulator

bound states

$2e^-$ (boson)

energy
doped Mott insulator

\{ free \}

\{ bound states \}

\{ 2e^- (boson) \}

energy
new model of doped Mott insulator
new model of doped Mott insulator
new model of doped Mott insulator

control parameter

bound

T
new model of doped Mott insulator

T

control parameter

bound

unbound (strange metal)
new model of doped Mott insulator

bound

unbound (strange metal)

(pseudogap)
new model of doped Mott insulator

bound

unbound (strange metal)

(pseudogap)
new model of doped Mott insulator

dictionary:

\( T^* \)

bound (pseudogap)

unbound (strange metal)

\( \text{control parameter} \)

hole

\( 2e \) boson

= hole

= 2e boson
new model of doped Mott insulator

\[ \rho \propto T \]

\( T^* \)

control parameter

bound

unbound (strange metal)

(pseudogap)

\( \circ = \text{hole} \)

\( \bullet = \text{2e boson} \)

dictionary:
Mottness: Strong Coupling

low-energy reduction

composite or bound states not in UV theory

Pseudogap=confinement
Key Experimental Prediction:

More particle addition states at low temperature than at high ($T^*$)
superconductivity?
superconductivity?

Thanks to: T.-P. Choy, R. Leigh, NSF
Superconductivity: Powering the Future

- 1986: First HTS (high-temperature superconducting) wire made.
- 1987: Initial HTS (high-temperature superconducting) wire demonstrated.
- 1988: First HTS (high-temperature superconducting) wire manufactured.
- 1989: First HTS (high-temperature superconducting) wire manufactured.
- 1990: World's first synchronous motor using HTS (high-temperature superconducting) wire demonstrated.
- 1993: World's first HTS (high-temperature superconducting) motor demonstrated.
- 1996: World's first HTS (high-temperature superconducting) motor demonstrated.
- 1997: World's first HTS (high-temperature superconducting) motor demonstrated.
- 1999: World's first HTS (high-temperature superconducting) motor demonstrated.
- 2000: World's first HTS (high-temperature superconducting) motor demonstrated.

U.S. Department of Energy
The image shows a temperature chart with various compounds and their corresponding years of discovery. The compounds include:

- HgBa$_2$Ca$_2$Cu$_3$O$_8$ (1987)
- Hg$_{0.8}$Tl$_{0.2}$Ba$_2$Ca$_2$Cu$_3$O$_8+x$ (1987)
- TlCaBaCuO
- YBCO
- Nb$_3$Ge
- V$_3$Si
- Ni
- Hg

The chart illustrates the timeline of superconductivity discoveries, starting from 1910 with Hg and ending with TlCaBaCuO in 1987. It also highlights the development of Fe-based cuprates.
Temperature (K)

- Hg
- Ni
- NbN
- V$_3$Si
- Nb$_3$Ge
- HgBa$_2$Ca$_2$Cu$_3$O$_8$
- TlCaBaCuO
- Hg$_{0.8}$Tl$_{0.2}$Ba$_2$Ca$_2$Cu$_3$O$_{8+x}$

Year

- 1910
- 1932
- 1943
- 1954
- 1976
- 1987
- 2010

Nitrogen liquifies at 77K

Cuprates

Fe-based
Temperature (K)

Year


V$^3$Si

Nb$^3$Ge

HgBa$_2$Ca$_2$Cu$_3$O$_8$

Hg$_{0.8}$Tl$_{0.2}$Ba$_2$Ca$_2$Cu$_3$O$_{8+x}$

Iron-based cuprates

Nitrogen liquifies at 77K