New Quantum States of Matter

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- new states at Quantum Phase Transitions
  - Superconductors,
    superinsulators, nematics, BEC’s

- Fermi surface reconstruction and high temperature superconductivity
A brief history of new states in condensed matter:

- Crystalline order (Von Laue 1914)
- Superconductivity (Kammerlingh Onnes 1913)
- Superfluidity (4He) (Kapitza 1978)
- Antiferromagnetism (Neel 1970)
- Superfluidity (3He) (Lee, Richardson, Osheroff 1996)
- Fractional quantum Hall state (Laughlin, Stormer, Tsui 1998)
- High Tc superconductivity (Bednorz, Mueller 1987)
- Bose-condensates (Cornell, Ketterle, Weiman 2001)
- (graphene) (Geim, Novosolov, 2010)
New Materials

• Compared to biology, materials preparation in quantum condensed matter is
  – Small-scale
  – Slow
  – comparatively unsophisticated (very little automation)
• Greater use of electronic structure calculations?
• Automation?
• Pressure?
Superconducting elements under very high pressure

Shimizu et al., JPSJ 74 (2005) 1345.
high temperature superconductivity

Battlogg and Varma, Physics World, Feb. 2000

JC Davis web site
American Superconductor Corporation (NASDAQ: AMSC), a global power technologies company, today announced that it has received the world's largest order for high temperature superconductor (HTS) wire. LS Cable Ltd. (LS Cable), the world's third largest power cable manufacturer, has placed an order for 3 million meters (nearly 10 million feet) of Amperium wire - AMSC's proprietary second generation (2G) HTS wire. (6 Oct 2010)
CePd$_2$Si$_2$

- Crystal structure common to many heavy fermion alloys
- Antiferromagnetic below $T_N=10K$, with an ordered moment of $0.7\mu_B$
- Pressure suppresses magnetic order

CePd$_2$Si$_2$ phase diagram

$T_N \propto (p_c - p)$

$\rho \propto T^{1.4}$

quantum critical point.

Other quantum critical superconductors

Saxena et al., Nature 2002

CeIn$_3$

BaFe$_2$As$_2$
Chu et al. 2009

CeCu$_2$Si$_2$

Yuan et al., Science 2003
Metamagnetic quantum phase transition

Sr$_3$Ru$_2$O$_7$

Electron nematic at a metamagnetic instability

Grigera et al. Science 2003
Borzi et al. Science 2006
Rost et al. Science 2009
Superinsulator at the superconductor-insulator boundary

Vinokur et al., Nature 2008
BEC of triplons


triplet-singlet energy

S = Nk ln 2

H_L  H_c  H_U
\( S = N k \ln 2 \)
“Algorithm” for discovering a new state of condensed matter:

• Take a very pure material with some kind of order (e.g. magnetic)
• Apply pressure or magnetic field etc. to suppress the order (produce a highly degenerate state with strong interactions to mediate new order)
• Cool to low temperature (to get rid of thermal noise, allow fragile quantum states to emerge)
Why “Quantum” Phases?

bosons

fermions

pairing
Electron quasiparticle in a magnetic field
Crossing of Zeeman-split crystal field levels leads to large region of AFQ order at high magnetic field.

\[ \Gamma_3 \]
\[ \Gamma_4 \]

65 K

6 K

\[ \Gamma_5 \]
\[ \Gamma_1 \]

Small to Large Fermi surface transition

(a) LaRhIn$_5$ (CeRhIn$_5$)

(b) CeCoIn$_5$

Knebel, JPSJ 2008

Harima et al., JPSJ 74 (2005) 1103.
Is high temperature superconductivity the response of a metal when it doesn’t know what it’s Fermi surface should be?
Conclusions

• Quantum phase transitions offer a natural place to look for new quantum states of matter
• Exotic superconductivity is not rare, but it is usually fragile
• Quantum magnetism has emerged as a field of central importance
• Fermi surface instabilities may be the key to finding new high temperature superconductors