Quantum phase transitions and novel phases in condensed matter

Thomas Vojta
Department of Physics, Missouri University of Science and Technology

- Condensed matter physics: complexity and emerging phenomena
  - Phase transitions and quantum phase transitions
  - Novel phases close to quantum critical points

Belo Horizonte, April 24, 2015
Acknowledgements

At Missouri S&T:

- Rastko Sknepnek, PhD '04
- José Hoyos, Postdoc '07
- Chetan Kotabage, PhD '11
- David Nozadze, PhD '13
- Fawaz Hrahsheh, PhD '13
- Manal Al Ali, PhD '13
- Hatem Barghathi

Experimental Collaborators:

- Almut Schroeder (Kent State)
- Istvan Kezsmarki (TU Budapest)
What is condensed matter physics?

Condensed Matter Physics (Wikipedia):

*deals with the macroscopic properties of matter; in particular ... the “condensed” phases that appear whenever the number of constituents in a system is large and their interactions ... are strong

Traditionally: Physics of solids and liquids

• What is the structure of crystals?
• How do solids melt or liquids evaporate?
• Why do some materials conduct an electric current and others do not?

Today: all systems consisting of a large number of interacting constituents

• biological systems: biomolecules, DNA, membranes, cells
• geological systems: earthquakes
• economical systems: fluctuations of stock markets, currencies
Why condensed matter physics?

Applications: "Helps you to make stuff."

- semiconductors, transistors, microchips
- magnetic recording devices
- liquid crystal displays
- plastic and composite materials

Maglev train using levitation by superconducting magnets, can go faster than 350 mph

Read head, based on Giant Magnetoresistance effect (A. Fert + P. Grünberg, Physics Nobel Prize 2007)
Directions of fundamental physics research:

Astrophysics and cosmology:
increasing length and time scales
“physics of the very large”

Atomic, nuclear and elementary particle physics:
decreasing length and time scales
“physics of the very small”

What fundamental direction does condensed matter research explore?
“physics of the very complex”
Emerging phenomena:

When **large numbers** of particles strongly **interact**, qualitatively new properties of matter **emerge** at every level of complexity.
Where to look for new phenomena and novel phases?

- **at low temperatures**
  
  \[ F = E - TS \]

  - thermal motion is suppressed
  - new types of order can form

- **at boundaries of existing phases**

  - two types of order compete, suppress each other
  - novel type of order may appear
Wonderland of low temperatures

273K (0°C)  water freezes
195K (-78°C)  carbon dioxide sublimates (dry ice)
133K (-140°C)  superconductivity in cuprate perovskites
77K (-196°C)  nitrogen (air) liquefies
66K (-207°C)  nitrogen (air) freezes
4.2K (-268.9°C)  helium liquefies
2.2K (-270.9°C)  helium becomes superfluid
170 nK  Bose-Einstein condensation of rubidium
0K (-273.1°C)  absolute zero of temperature

* Nandini Trivedi
- Condensed matter physics: complexity and emerging phenomena
- **Phase transitions and quantum phase transitions**
  - Novel phases close to quantum critical points
Phase transition:
singularity in thermodynamic quantities as functions of external parameters
Phase transitions: 1st order vs. continuous

1st order phase transition:
phase coexistence, latent heat, short range spatial and time correlations

Continuous transition (critical point):
no phase coexistence, no latent heat, infinite range correlations of fluctuations

Critical behavior at continuous transitions:
diverging correlation length $\xi \sim |T - T_c|^{-\nu}$ and time $\xi_T \sim \xi^z \sim |T - T_c|^{-\nu z}$
• Manifestation: critical opalescence (Andrews 1869)

Universality: critical exponents are independent of microscopic details
Critical opalescence

**Binary liquid system:**

e.g. hexane and methanol

\[ T > T_c \approx 36^\circ C: \text{fluids are miscible} \]

\[ T < T_c: \text{fluids separate into two phases} \]

\[ T \rightarrow T_c: \text{length scale } \xi \text{ of fluctuations grows} \]

When \( \xi \) reaches the scale of a fraction of a micron (wavelength of light):

**strong light scattering**

**fluid appears milky**

Pictures taken from [www.physicsofmatter.com](http://www.physicsofmatter.com)
How important is quantum mechanics close to a critical point?

Two types of fluctuations:

- thermal fluctuations (thermal motion), energy scale $k_B T$
- quantum fluctuations (quantum zero-point motion), energy scale $\hbar \omega_c$

Quantum effects unimportant if $\hbar \omega_c \ll k_B T$.

Critical slowing down:

$$\omega_c \sim 1/\xi \sim |T - T_c|^{\nu z} \to 0 \text{ at the critical point}$$

⇒ For any nonzero temperature, quantum fluctuations do not play a role close to the critical point
⇒ Quantum fluctuations do play a role at zero temperature

Thermal continuous phase transitions can be explained entirely in terms of classical physics, zero-temperature transitions require quantum mechanics
Quantum phase transitions

occur at **zero temperature** as function of pressure, magnetic field, chemical composition, ...

**driven by quantum zero-point motion** rather than thermal fluctuations

Phase diagrams of LiHoF\(_4\) and a typical high-\(T_c\) superconductor such as YBa\(_2\)Cu\(_3\)O\(_{6+x}\)
Toy model: transverse field Ising model

Quantum spins $S_i$ on a lattice: (c.f. LiHoF$_4$)

$$H = -J \sum_i S^z_i S^z_{i+1} - h \sum_i S^x_i$$

$$= -J \sum_i S^z_i S^z_{i+1} - \frac{h}{2} \sum_i (S^+_i + S^-_i)$$

$J$: exchange energy, favors parallel spins, i.e., ferromagnetic state
$h$: transverse magnetic field, induces quantum fluctuations between up and down states, favors paramagnetic state

**Limiting cases:**

$|J| \gg |h|$ ferromagnetic ground state as in classical Ising magnet

$|J| \ll |h|$ paramagnetic ground state as for independent spins in a field

$\Rightarrow$ **Quantum phase transition** at $|J| \sim |h|$ (in 1D, transition is at $|J| = |h|$)
**Magnetic quantum critical points of TlCuCl$_3$**

- TlCuCl$_3$ is magnetic insulator
- planar Cu$_2$Cl$_6$ dimers form infinite double chains
- Cu$^{2+}$ ions carry spin-1/2 moment

**antiferromagnetic order** can be induced by
- applying pressure
- applying a magnetic field
Pressure-driven quantum phase transition in TICuCl$_3$

quantum Heisenberg model

\[ H = \sum_{\langle ij \rangle} J_{ij} \vec{S}_i \cdot \vec{S}_j - \vec{h} \cdot \sum_i \vec{S}_i . \]

\[ J_{ij} = \begin{cases} J & \text{intra-dimer} \\ J' & \text{between dimers} \end{cases} \]

pressure changes ratio $J/J'$

**Limiting cases:**

$|J| \gg |J'|$ spins on each dimer form singlet $\Rightarrow$ no magnetic order

low-energy excitations are “triplons” (single dimers in the triplet state)

$|J| \approx |J'|$ long-range antiferromagnetic order (Néel order)

low-energy excitations are long-wavelength spin waves

$\Rightarrow$ quantum phase transition at some critical value of the ratio $J/J'$
Field-driven quantum phase transition in TlCuCl$_3$

**Single dimer in field:**
- field does not affect singlet ground state but splits the triplet states
- ground state: singlet for $B < B_c$ and (fully polarized) triplet for $B > B_c$

**Full Hamiltonian:**
- singlet-triplet transition of isolated dimer splits into two transitions
- at $B_{c1}$, triplon gap closes, system is driven into ordered state (uniform magnetization $||$ to field and antiferromagnetic order $\perp$ to field)
- “canted” antiferromagnet is Bose-Einstein condensate of triplons
- at $B_{c2}$ system enters fully polarized state
Superconductor-metal QPT in ultrathin nanowires

- ultrathin MoGe wires (width $\sim 10$ nm)
- produced by molecular templating using a single carbon nanotube
  [A. Bezryadin et al., Nature 404, 971 (2000)]

- thicker wires are superconducting at low temperatures
- thinner wires remain metallic

superconductor-metal QPT as function of wire thickness
Pairbreaking mechanism

- pair breaking by surface magnetic impurities
- random impurity positions
  ⇒ quenched disorder
- gapless excitations in metal phase
  ⇒ Ohmic dissipation

weak field enhances superconductivity

magnetic field aligns the impurities and reduces magnetic scattering
Mott transition in a Bose-Einstein condensate
• Condensed matter physics: complexity and emerging phenomena
  • Phase transitions and quantum phase transitions
  • Novel phases close to quantum critical points
Magnetic phases in MnSi

Phase diagram: (Pfleiderer et al, 2004)

- magnetic transition at 30 K at ambient pressure
- transition tunable by hydrostatic pressure
- quantum phase transition at $p_c = 14$ kbar

Magnetic state:

- ordered state is helimagnet with $q = 180\,\text{Å}$, pinned in (111) direction
- short-range order persists in paramagnetic phase, helical axis depinned
Skyrmions and skyrmion lattices

- even more exotic magnetic states occur in magnetic field $B$
- in “A” phase, magnetization vector forms knots, called skyrmions, by twisting in two directions
- these skyrmions arrange themselves into regular skyrmion lattice
Exotic superconductivity in UGe$_2$

**Phase diagram:**

- phase diagram of UGe$_2$ has pocket of **superconductivity** close to ferromagnetic quantum phase transition (electrical resistivity **vanishes** below about 1K)
- in this pocket, UGe$_2$ is **ferromagnetic and superconducting** at the same time
- superconductivity appears only in superclean samples

Phase diagram and resistivity of UGe$_2$ (Saxena et al, Nature, 2000)
Character of superconductivity in UGe$_2$

not compatible with conventional (BCS) superconductivity:

- in superconductor, electrons form (Cooper) pairs of spin-up and spin-down electrons
- ferromagnetism requires majority of spins to be in one direction

theoretical ideas:

- phase separation (layering or disorder): NO!
- partially paired FFLO state: NO!
- spin triplet pairs with odd spatial symmetry, magnetic fluctuations promote this type of pairing

Magnetic quantum phase transition induces spin-triplet superconductivity
Is high-temperature superconductivity caused by QPT?

Phase diagram for a high-$T_c$ superconductor such as $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$.
Conclusions

• emerging phenomena: “more is different”

• new states of matter often can be found at low temperatures and at boundaries between existing phases

• quantum phase transitions occur at zero temperature as a function of a parameter like pressure, chemical composition, disorder, magnetic field

• quantum phase transitions are caused by quantum fluctuations (i.e., Heisenberg’s uncertainty principle) rather than thermal fluctuations

• quantum phase transitions can have fascinating consequences including the genesis of new phases

Quantum phase transitions provide a novel ordering principle in condensed matter physics
If the critical behavior is classical at any nonzero temperature, why are quantum phase transitions more than an academic problem?
Quantum critical point controls **nonzero-temperature** behavior in its vicinity:

**Path (a):** crossover between classical and quantum critical behavior

**Path (b):** temperature scaling of quantum critical point