PHYS 610 (4/1/09): Overview of Research in Quantum Info / Mechanics

- Experiments & expt-related theory
- Incomplete, influenced by my taste / knowledge, big "field" (many fields)

I. Quantum Computing

A. Quantum Simulator

- Universal Quantum Simulator (Feynman, 1982) for many interacting quantum systems
    - classical computer → exponential slowdown (with N) for simulating large quantum system (N qubits much more info than N bits)
        - qubit = 2 level quantum system
        - e.g., entanglement
    - quantum computer → no need for such slowdown
    - more realistic → "application-specific analog computers" for quantum many-body problems
        - ultracold (degenerate) bosonic / fermionic atoms in optical lattices
            - study phase transitions, hard to do theoretically
                (Stamper-Kurn, Lev, Bloch, Jin, Ketterle, Grimm)
                - Stamper-Kurn ↑ spinor BEC
                - Lev ↑ exotic phases
                - Bloch ↑ Mott-insulator transition
                - Jin, Ketterle, Grimm: BEC-BCS
            - esp. for fermions (antisymmetrization), models of high-T_c superconductors
        - ion-trap arrays (Chuang, theory: Ortiz, Knill) → universal simulators with 2-ion interactions

I. Quantum Computing (cont'd)

B. Universal Quantum Computation

- use qubits and quantum logic gates, quantum version of classical digital computation (Deutsch, 85), perform arbitrary quantum calculations.

- Shor's algorithm → factorize integers, classical → not polynomial time (< exp)
  quantum → polynomial time
  - realized via NMR (no entanglement), photons.
  - main driving force in field (funding, cryptography).
- Grover's algorithm → search database in $O(\sqrt{N})$ time (QM) vs. $O(N)$ (CM)
- Deutsch - Jozsa algorithm → abstract, not practical, but shows QC more efficient than CC
- Quantum Fourier transform → implemented classically (e.g. lens imaging)
- adiabatic quantum computation → prepare known gnd state of H_1
  adiabatically map $H_1 \to H_2$
  get gnd state of H_2 (possibly complicated)
- other quantum algorithms? (not many)
- cluster states

C. Realizations of Qubits, Gates, Scalable Computers

- Quantum Computation Roadmap (2004) http://qist.lanl.gov/[illegible]
  ↓
- "DiVincenzo criteria:"
  1. scalable physical system of well-characterized qubits
  2. ability to initialize state of qubits
  3. long decoherence times (>> gate time)
  4. universal set of quantum logic gates
  5. qubit-specific readout

  also for networkability

  6. ability to interconnect stationary and "flying" qubits
  7. ability to faithfully xmit flying qubits

C. Realizations (cont'd)

- NMR (e.g., molecules in liquid state) → not scalable or networkable
  (Laflamme, Chuang, Nielsen) (no entanglement)
- Trapped Ions → promising
  - linear ion trap → Cirac-Zoller scheme (limited scalability)
  - "ion CCD array" → segmented trap to maneuver many ions between storage and accumulator regions, scalable (Wineland, Monroe groups → learning to move ions
  - entanglement production (Blatt, Wineland) in T, X-junctions)
- Neutral atoms in optical lattices (I. Deutsch & Jessen, proposal)
  - expts: Jessen, Phillips → very hard
  - Deutsch: Group II atoms, can laser cool + preserve quantum info.
  - Weiss group: imaging atoms in 3D lattice
  - Hänsch, Esslinger - compactification of atoms in lattice (proposal) - collisions
  - Rydberg blockade (Walker?)
- optical (photons) (Rayner, Kwiat, Zeilinger, White, Pryde?, Gisin
  - good for communication
  - need quantum repeater
  - linear optics quantum computation (Knill, Laflamme, Milburn) ← efficient
    - cluster states → more efficient (Zeilinger) "KLM" is inefficient..
    - gates require interactions → nonlinear Hamiltonians, products of operators
      clever idea:
      - get nonlinear interactions via measurement & postselection
    - hard to scale w/ postselection

- solid-state qubits: quantum dots, diamond NV centers (artificial atoms)
  ↖ decoherence may be problem
  - Solid-state NMR (Kane)

- superconducting qubits / Josephson junctions (e.g., Martinis), D-Wave
  - cooper pair boxes (Kouwenhoven)
- topological quantum computation
- stripline resonator cavity QED (microwaves)
- spintronics (Imamoglu, Awschalom, Crooker)

I. Quantum Computing (cont'd)

D. Error Correction

- large, universal computation → need to correct gate errors (or small)
  (expts have ~ 99% fidelity, should do much better)
- simulation → need correction above ~ 50 spins
- demonstration, e.g. in ions (Wineland)
- robust unitary transformations in NMR, compensate for inhomogeneous broadening (apply to ions → Chuang)
- how many ions? Zalka, Chuang

E. Quantum Communication

- quantum teleportation → transfer state of one qubit to another via entanglement
  (e.g. share entangled pair, transmit only classical info)
  - no-cloning, not classical

  (Zeilinger, Kimble, Wineland)
  photons (Zeilinger, Kimble); ions (Wineland)
- bit commitment
- remote coin tossing
- QKD, secret sharing (Hughes, many others)
- quantum networks
  - need highly efficient coupling between atom & photon
    hard: atom cross-section $\sim \frac{\lambda^2}{2\pi} \sim \frac{(\text{few} \times 10^{-7}\text{m})^2}{2\pi} \sim 10^{-9}\text{cm}^2$
  - cavity QED → single atom in ultrahigh-finesse cavity
    strong coupling if cavity decay very slow
  - free-space → highly focused beams (theory → van Enk, expts too ← Sandoghdar, Kurtsiefer).
  - recent: Kimble, cavity QED w/ micro toroids, many others.

II Precision Metrology

A. Standard Quantum limit for measurements

- uncertainty of harmonic oscillator
- many particles, e.g. in interferometer, $\sim \sqrt{N}$ (independent ptles)

B. sub-SQL (e.g. interferometry)

- scales as $\sim N$ (Heisenberg limit) → imposed by quantization of matter/light.
  (smallest subdivision of sample)
- e.g. proposals by Holland, Burnett, Kasevich
- photons → Pryde

II. Precision Metrology (cont'd)

C. sub-Heisenberg (Geremia, Caves)

D. Applications: interferometry (gravity), magnetometry, ~~[illegible]~~
(Kasevich → atom interferometry)

E. time & frequency metrology: Al+ clock (application of logic gates)
error = $\frac{\delta\omega}{\omega}$ ω large → UV transition! use Be+
- optical lattice clocks (Sr, Ye) (Bergquist / Wineland)

III Decoherence, Mesoscopic QM

- how big can an object be and still be quantum? (Leggett: QM changes in macro regime?).
  - Zeilinger → bucky balls in interferometer
  - nanomechanical resonators (Schwab, Roukes), membranes (Harris)
    (not quantum yet, but close).
    - microspheres (Wang)
    - toroids (Kippenberg, Vahala)
  - entanglement of atomic vapors
    (Ragnar)
    Polzik

IV Quantum Control

- map |ψ⟩ → |ψ'⟩ (known initial condition), need proper unitary evolution
  (Rabitz).
- learning control → repeat ↑ many times, use genetic optimization to produce map (engineered chemical reactions via shaped pulsed lasers, Rabitz).
- quantum feedback control
  - unknown initial state
  - continuous measurements, feed back based on measurement info
    (Wiseman, Mabuchi)
  - adaptive measurement experiment (Mabuchi)
  - coherent feedback (quantum feed back channel)
    recent expt → Mabuchi

V Quantum Measurements and Dynamics

- Quantum chaos (fidelity, tunneling)
- continuous measurement of spin ensemble (Jessen, Mabuchi)
- weak measurements (Jessen)
- continuous measurement of photon # in cavity w/ Rydberg atoms (Haroche)
- quantum jumps in ions (Wineland, Blatt, Dehmelt, Bergquist).
- quantum Zeno effect (Wineland, Raizen)
- undoing quantum measurement (Korotkov)

VI Misc.

- indistinguishability of quantum particles (Hau)
- Casimir effects
- vortices in BECs (Dalibard, Cornell, Ketterle)