Atomic and Molecular Physics Program

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**Atomic and Molecular Physics Program**

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BRIEF DESCRIPTION OF PORTFOLIO:
Understanding interactions between atoms, molecules, ions, and radiation.

SUB-AREAS IN PORTFOLIO:
• Cold Quantum Gases
  – Strongly-interacting quantum gases
  – Ultracold molecules
  – New phases of matter
  – Non-equilibrium quantum dynamics
• Quantum Information Science (QIS)
  – Quantum simulation
  – Quantum communication
  – Quantum metrology, sensing, and imaging
  – Cavity optomechanics
Outline

• **Quantum Communication: Quantum Memories and Light-Matter Interfaces (FY11 MURI)**
  - Strongly Interacting Photons: Vladan Vuletic (MIT)
    • Cavity-based single-photon transistor where one photon can switch 1000 photons: Wenlan Chen, *et al*, *preprint*
  - Atomic Quantum Memories in Nano-Scale Optical Circuits: Jeff Kimble, Oskar Painter (CalTech)
    • PMMA-diamond hybrid cavities, coupling stable NV centers
  • **Cavity Optomechanics with Cold Atoms**: Dan Stamper-Kurn (UC Berkeley)
  • **Ultracold Molecules**: Jun Ye, John Bohn (JILA)
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Quantum Networks

Enable ultra-secure communication over fiber network or free space

Site A

Quantum Repeater

Entanglement

Site B

Requirements
• Light-matter interface
• Quantum memory
• Elementary quantum gates

Quantum Memories and Light-Matter Interfaces (FY11 MURI)

- Memory-light entanglement;
- Deterministic quantum gates;
- Long memory lifetime;
- Memory coupling to telecom light;
- Cavity-enhanced light-memory coupling.
Quantum Memories and Light-Matter Interfaces (FY11 MURI)

- **Two teams:**

- **Accomplishments in 1st year:**
  
  **Atoms:**
  - 16s atomic memory (GaTech)
  - Rydberg single-photon source (GaTech)
  - Nonlinearity at the single-photon level (MIT/Harvard)
  - Single-photon transistor (MIT)
  - Coupling atoms with nanofiber cavities (CalTech)
  - Atomic mirrors, integration with nanophotonics (CalTech)

  **Quantum dots:**
  - New scheme to efficiently couple a single QD electron spin to an optical nanocavity (Stanford)

  **NV-diamond:**
  - Spin-photon interface: quantum interference demonstrated (Harvard)
  - NV qubit coherence lifetime > 1s (Harvard)
  - All-optical control of NV spins (UCSB)
  - Stable NV centers in bulk and nanobeams
  - Integrated diamond networks for nanophotonics (Harvard)
  - Engineering shallow spins with N delta-doping (UCSB)
  - SiC and other color centers (UCSB, U. Iowa)

- **More than 40 papers, including 6 Nature/Science and 10 PRLs.**
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Photon-photon switch and transistor
Vladan Vuletic, MIT

Experimental setup

Atomic level scheme

Wenlan Chen, et al, preprint
Single-photon transistor with gain: switching 1000 photons with one

Single gate photon suppresses signal transmission by factor of 6.

More than 1000 signal photons can be blocked by a single photon!
Future Possibilities

- Quantum non-demolition detector for traveling optical photons
- Deterministic photon-photon phase shift
- Photon-photon quantum gates?
- All-optical circuits with feedback and gain in analogy to electronic circuits
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Nanofiber Optical Trap for Cold Atoms
Jeff Kimble, CalTech

- Strong interactions of single photons and atoms
  - Multi-pass interactions and small mode volume in an optical cavity (cQED)
  - Large optical depth (e.g., atomic ensembles)
  - Strong focusing of light

- A new frontier to achieve all three in one setting — nanofiber atom trap
Demonstration of a State-Insensitive Nanofiber Trap


Nano-fiber

~1000 atoms

$E_{\text{in}}$  $E_{\text{reflected}}$  $E_{\text{transmitted}}$
**Cavity QED with Atomic Mirrors**


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**Quantum protocols**
- Single photon generation
- Entanglement distribution
- Quantum logic
  - atoms
  - photons
  - ...

**Nanofiber issues**
- Two-color traps increase noise sensitivity
- Ill defined polarizations for trap and probe fields
- “Noise” from vibrational modes of nanofiber...

**A Surprise!**
- Strong coupling regime can be reached with very low cavity finesse $F < 10^3$
- Conventional Fabry-Perot cavity with dielectric mirrors requires finesse $F \approx 10^5$

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**Cavity QED**

[Diagram showing input and output ports with atoms and mirrors]
• Clear window for trapping of atomic clouds in Kimble Group MOT

• Arrays of fiber-coupled waveguides (1 shown here) for multiple device testing in a given experiment run

Efficient collection fiber

Evanescent atom-light coupling

Photonic crystal mirrors/cavities
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NV centers provide
• Room temperature quantum coherence
• Long spin coherence ($T_2 \approx 10$ ms)
• Optical initialization and readout
• Solid state system
• Reduced nuclear spin environment

Challenges for quantum information processing:
• Creating identical single spins
• Developing scalable quantum memories
• Fabricating hybrid devices
New approach for fabricating nanostructures from bulk diamond

Angle-Etched Diamond Nanobeam Cavities @ Telecom

Taper-fiber measurements in telecom

\[ Q_{1,\text{exp}} \sim 20\,000 \]
\[ Q_{2,\text{exp}} \sim 5\,000 \]
Challenge: spatial & spectral overlap between a stable NV and a cavity;

Solution:

• Deterministic positioning of cavities around NVs;
• New cavity approach that allows for cavities to be realized around the same NV multiple times;
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Cavity Optomechanics

Common goals:
- Dominance of quantum fluctuations over thermal fluctuations
  - cooling mechanical oscillator to ground state
  - reaching quantum limits for sensitivity
- Study and use quantum effects
  - quantifying and evading measurement backaction
  - entanglement of macroscopic object with light
- Route to complex quantum systems
  - Multi-mode systems (optics and mechanics)
  - Optomechanics as link between quantum objects

Kippenberg and Vahala, Science 321, 1172 (2008)
Each ensemble represents a mechanical element

Mechanical oscillator: sheets of atoms

trap
probe

\[ \begin{align*}
Z_1 & \quad Z_2 & \quad Z_3 \\
& & & \text{trapped ultracold rubidium atoms}
\end{align*} \]

2mm

MOT Loading

Conveyor Belt

Cavity Locations

DISTRIBUTION STATEMENT A – Unclassified, Unlimited Distribution
Non-classical light generation

Input = AM tone to measure gain
Input = vacuum noise to measure squeezing

Sub-shot-noise optical squeezing observed

Below shot-noise by
1.4% ±0.1% (stat) ±0.1% (sys)


- Collective atomic motion is driven by quantum fluctuations in radiation pressure
- The back-action of this motion onto the cavity light field produces *ponderomotive squeezing*
Next: Cavity optomechanics with a mechanical array


- Nearby lattice sites given different resonances using optical superlattice
- Sideband asymmetry for each oscillator
- 6 mechanically distinct oscillators demonstrated
- Motional state of one oscillator can be selectively addressed
- Nanometer-scale spatial resolution of each mechanical element
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Science with Ultracold Molecules


- Novel phases & quantum many-body
- Dipolar quantum gas
- Quantum information
- Ultracold Chemistry

- Molecule optics & circuitry
- Cold controlled chemistry

- Novel collisions
- Fundamental tests
- Precision measurement

Phase space density

$\log_{10}(\text{density [cm}^{-3}\text{])}$

$\log_{10}(\text{temperature [K]})$
Evaporative Cooling of OH
Jun Ye, John Bohn, JILA

Cooling by at least an order of magnitude in temperature and three orders in phase space density!!