Quantum Information Science with AMO

implementation …

• new AMO systems in lab → quantum info
• new “scenarios”

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Innsbruck: collaborations:
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Friday, April 24, 2009
(Stroboscopic) Coherent and Dissipative Quantum Simulations with Rydberg Atoms

(or: polar molecules / trapped ions)

“exotic” many body spin systems with many body interactions / constraints

Generation of

\[ X X X X X X \quad (X = \sigma_x) \]

\[ Z Z Z Z Z Z Z \]

... interactions or constraints

Possible models: Kitaev toric code model, color codes, lattice gauge theories
(Stroboscopic) Coherent and Dissipative Quantum Simulations with Rydberg Atoms

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Topic 2:

AMO - Solid State Hybrid Systems

- strong coupling of single atom via photons to nanomechanical oscillator

see also M. Lukin’s talk

Caltech + JILA + Innsbruck
Topic 1: Quantum Simulations

how?

• coherent & dissipative
• “analogue” & “digital” simulation

why?

• cond mat
• simulate exotic material
• prepare entangled state (as resource)
Coherent Quantum Dynamics

- “analogue” simulation
  - We “build” a quantum system with desired dynamics & controllable parameters, e.g. Hubbard models of atoms in optical lattices
  - [We know how to prepare (cool to) its ground state]
  - exp.: almost all cold atom labs, ...

It is difficult to mimic n-body interactions & constraints

\[ V^{(n)} \sim V^{(2)} \frac{1}{E - H} V^{(2)} \ldots V^{(2)} \frac{1}{E - H} V^{(2)} \rightarrow "0" \]

n-body  2-body  effective n-body interactions in extended Hubbard models

perturbation theory
Coherent Quantum Dynamics

• “stroboscopic” or “digital” simulation

stroboscopic time evolution as sequence of quantum gates

qubits or spins

single qubit gate 2-qubit gate n-qubit gate ~ n-body interaction

time

$e^{-iH_{\text{eff}}t}$

desired many body Hamiltonian “on the average”
Q.: errors?

Lloyd, ...
Coherent Quantum Dynamics

- "digital" simulation

stroboscopic time evolution as sequence of quantum gates

\[ e^{-iH_{\text{eff}} t} \]

qubits or spins

single qubit gate 2-qubit gate n-qubit gate ~ n-body interaction

spin-dependent optical lattice

\[ \alpha | \uparrow \rangle + \beta | \downarrow \rangle \]

qubits on a lattice

entangling qubits via "Ising" (cluster state)

desired many body Hamiltonian “on the average”

Q.: errors?

exp.: Bloch, Meschede, ...

Lloyd, ...
Coherent Quantum Dynamics

- "digital" simulation

\[ e^{-iH_{\text{eff}}t} \]

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Lloyd, ...
Coherent Quantum Dynamics

- “digital” simulation

**stroboscopic time evolution as sequence of quantum gates**

- single qubit gate
- 2-qubit gate
- n-qubit gate \( \sim n\)-body interaction

\[ e^{-iH_{\text{eff}}t} \]

**spin-dependent optical lattice**

- qubits on a lattice
- entangling qubits via "Ising" (cluster state)

- desired many body Hamiltonian “on the average”
- Q.: errors?

exp.: Bloch, Meschede, ...

Lloyd, ...

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Open Quantum Systems

- Q.: dissipative preparation of entangled states

$$\rho \rightarrow \mathcal{E}(\rho) = \sum_{k} E_k \rho E_k^\dagger$$

B. Kraus et al., PRA 2008
[see also: Verstraete, Cirac et al. 2008]
Open Quantum Systems

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Open Quantum Systems

- Q.: dissipative preparation of entangled states

\[
\rho \rightarrow \mathcal{E}(\rho) = \sum_k E_k \rho E_k^\dagger
\]

- Optical pumping (Kastler) or laser cooling

\[
\rho(t) \xrightarrow{t \to \infty} |g_+\rangle \langle g_+|
\]

Driven dissipative dynamics "purifies" the state

B. Kraus et al., PRA 2008
[see also: Verstraete, Cirac et al. 2008]
Open Quantum Systems

• Q.: dissipative preparation of entangled states

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n-body quantum jump operators

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[see also: Verstraete, Cirac et al. 2008]
Open Quantum Systems

- Q.: dissipative preparation of entangled states

$$\rho \rightarrow \mathcal{E}(\rho) = \sum_k E_k \rho E_k^\dagger$$

- Lindblad master equation

$$\frac{d\rho}{dt} = -i [H, \rho] + \mathcal{L}\rho$$

B. Kraus et al., PRA 2008
[see also: Verstraete, Cirac et al. 2008]

Q.: engineer quantum reservoirs couplings?

n-body quantum jump operators 😞
Example: Kitaev Toric Code

- Kitaev

- toric code $|K\rangle$ with $\left\{ S_x^{(p)} |K\rangle = |K\rangle, S_z^{(s)} |K\rangle = |K\rangle \right\}$ for all $X$ and $Z$ stabilizers

- ground state of the Kitaev toric code Hamiltonian

$$H = -\hbar \sum_{\text{plaquette}} \sigma_x^{(1p)} \sigma_x^{(2p)} \sigma_x^{(3p)} \sigma_x^{(4p)} - \hbar \sum_{\text{star}} \sigma_z^{(1s)} \sigma_z^{(2s)} \sigma_z^{(3s)} \sigma_z^{(4s)}$$

$$= -\hbar \sum_p S_x^{(p)} - \hbar \sum_s S_z^{(s)}$$
Example: Kitaev Toric Code

- Kitaev

  four body interaction \( S_x = \sigma_x^{(1)} \sigma_x^{(2)} \sigma_x^{(3)} \sigma_x^{(4)} \)

- toric code \(|K\rangle\) with \( \left\{ S_x^{(p)} |K\rangle = |K\rangle, S_z^{(s)} |K\rangle = |K\rangle \right\} \) for all \( X \) and \( Z \) stabilizers

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H = -h \sum_{\text{plaquette}} \sigma_x^{(1_p)} \sigma_x^{(2_p)} \sigma_x^{(3_p)} \sigma_x^{(4_p)} - h \sum_{\text{star}} \sigma_z^{(1_s)} \sigma_z^{(2_s)} \sigma_z^{(3_s)} \sigma_z^{(4_s)} \\
= -h \sum_p S_x^{(p)} - h \sum_s S_z^{(s)}
\]

qubit atoms
Example: Kitaev Toric Code

- **Kitaev**

  four body interaction
  
  \[ S_x = \sigma_x^{(1)} \sigma_x^{(2)} \sigma_x^{(3)} \sigma_x^{(4)} \]
  
  \[ S_z = \sigma_z^{(1)} \sigma_z^{(2)} \sigma_z^{(3)} \sigma_z^{(4)} \]

- toric code \(|K\rangle\) with \( \left\{ S_x^{(p)} \left| K \right\rangle = \left| K \right\rangle, S_z^{(s)} \left| K \right\rangle = \left| K \right\rangle \right\} \) for all \( X \) and \( Z \) stabilizers

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\]

\[
= -h \sum_p S_x^{(p)} - h \sum_s S_z^{(s)}
\]
Example: Kitaev Toric Code

- **Kitaev**

  four body interaction

  \[
  S_x = \sigma^{(1)}_x \sigma^{(2)}_x \sigma^{(3)}_x \sigma^{(4)}_x \\
  S_z = \sigma^{(1)}_z \sigma^{(2)}_z \sigma^{(3)}_z \sigma^{(4)}_z
  \]

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  \]

  \[
  = -h \sum_p S^{(p)}_x - h \sum_s S^{(s)}_z
  \]

- Q.: can we simulate the toric code 4-body Hamiltonian? with Rydberg atoms & dipolar interactions

- Q.: can we prepare the ground state dissipatively?
Example: Kitaev Toric Code

- Rydberg implementation

qubit atoms

n-qubit gate

Rydberg controller

qubit 1
2
3
4
Example: Kitaev Toric Code

- Rydberg implementation

four-body interaction term via Rydberg dipole-dipole

\[ S_x = \sigma_x^{(1)} \sigma_x^{(2)} \sigma_x^{(3)} \sigma_x^{(4)} \]
Example: Kitaev Toric Code

- Rydberg implementation

Four-body interaction term via Rydberg dipole-dipole

\[ S_x = \sigma_x^{(1)} \sigma_x^{(2)} \sigma_x^{(3)} \sigma_x^{(4)} \]

... can be simulated with help of an auxiliary X-controller atom

n-qubit gate
Example: Kitaev Toric Code

- Rydberg implementation

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Example: Kitaev Toric Code

• pumping stabilizer states

\[ T_x : \rho_s \mapsto A_1 \rho_s A_1^\dagger + A_2 \rho_s A_2^\dagger \]

\[ A_1 = \frac{1}{2} (1 - S_x) = A_1^\dagger \]

\[ A_2 = \frac{1}{2} \sigma_z(i) (1 + S_x) \neq A_2^\dagger \]

if +1, do nothing

if -1, pump

4 & 5 body operators ☹

• n-qubit gate + optical pumping of the Rydberg atom
Building Block: n-qubit CNOT Rydberg Gate

- **gate: ingredients**
  - atoms in a large spacing optical lattice: addressability [D. Weiss]
  - Rydberg dipole-dipole

\[ G = |0\rangle_c \langle 0| \otimes 1 + |1\rangle_c \langle 1| \otimes \sigma_x^{(1)} \sigma_x^{(2)} \sigma_x^{(3)} \sigma_x^{(4)} \ldots \]

**features:**

- High fidelity even for moderately large # qubits
- Fast 3 laser pulses
- Long-range interactions
- Robust with respect to
  - inhomogeneities in the interparticle distances
  - variations in the interaction strengths
  - no mechanical effects
- experimentally realistic parameters

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1. Coherent Time Step

resource: our multi-qubit CNOT-gate

\[ G = |0\rangle_c \langle 0| \otimes 1 + |1\rangle_c \langle 1| \otimes \sigma_x \sigma_x \sigma_x \sigma_x \]

\[ \Psi' = U \Psi \]

\[ U = \exp(-iH\tau/\hbar) \]

with

\[ H = -\frac{\hbar \alpha}{\tau} \sigma_x \sigma_x \sigma_x \sigma_x \]

... and similar for \( ZZZZ \)

composed evolution

stroboscopic simulation
1. Coherent Time Step

**our multi-qubit CNOT-gate**

\[ G = |0\rangle_c \langle 0| \otimes 1 + |1\rangle_c \langle 1| \otimes \sigma_x^{(1)} \sigma_x^{(2)} \sigma_x^{(3)} \sigma_x^{(4)} \]

\[ U^{(c)}_{\pi/2} (U^{(c)}_{\pi/2})^{-1} \]

\[ |\pm\rangle = \frac{1}{\sqrt{2}}(|A\rangle \pm |B\rangle) \]

\[ \sigma_\pm |\pm\rangle = \pm |\pm\rangle \]
1. Coherent Time Step

our multi-qubit CNOT-gate

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\[ R = \exp(i\alpha \sigma_z^{(c)}) \]

small local rotation of the control atom

\[ \alpha \ll 1 \]
1. Coherent Time Step

our multi-qubit CNOT-gate

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\[ G = |0\rangle_c \langle 0| \otimes 1 + |1\rangle_c \langle 1| \otimes \sigma_x^{(1)} \sigma_x^{(2)} \sigma_x^{(3)} \sigma_x^{(4)} \]

undo the mapping step

\[ \tau \]

time

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small local rotation of the control atom

\[ R = \exp(i\alpha\sigma_z^{(c)}) \]

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composed evolution

\[ |\Psi'\rangle = U|\Psi\rangle \]

with

\[ H = -\frac{\hbar \alpha}{\tau} \sigma_x^{(1)} \sigma_x^{(2)} \sigma_x^{(3)} \sigma_x^{(4)} \]

\[ U \equiv \exp(-iH\tau/\hbar) \]
1. Coherent Time Step

our multi-qubit CNOT-gate

\[ G = |0\rangle_c \langle 0| \otimes 1 + |1\rangle_c \langle 1| \otimes \sigma_x^{(1)} \sigma_x^{(2)} \sigma_x^{(3)} \sigma_x^{(4)} \]

\[ U = \frac{1}{\sqrt{2}} (|A\rangle \pm |B\rangle) \]

\[ \alpha \ll 1 \]

\[ \sigma_{\pm} |\pm\rangle = \pm |\pm\rangle \]

\[ R = \exp(i\alpha \sigma_z^{(c)}) \]

\[ \text{small local rotation of the control atom} \]

\[ \text{stroboscopic simulation} \]

\[ \text{energy scale set by rotation angle } \alpha \text{ and gate duration } \tau \]
2. Dissipative Step

- map the eigenvalue information onto the controller

\[ S_x |\Psi\rangle = +1 |\Psi\rangle \quad S_x |\Psi\rangle = -1 |\Psi\rangle \]

Hilbert space of the four spins

\[ +1 \quad -1 \]

\[ |0\rangle, |1\rangle, |2\rangle, |3\rangle, |4\rangle \]

X-controller

|0\rangle |1\rangle |A\rangle |B\rangle

\[ |+\rangle \quad |\rangle \quad |\rangle \quad |\rangle \]

\[ 1 \quad 2 \quad 3 \quad 4 \]

|\Psi\rangle
2. Dissipative Step

map the eigenvalue information onto the controller

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Hilbert space of the four spins

\[ |0\rangle \quad |1\rangle \]

\[ U^{(c)}_{\pi/2} G (U^{(c)}_{\pi/2})^{-1} \]

X-controller

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Hilbert space of the four spins

\[ |0\rangle \quad |1\rangle \]

- Conditional spin flip of one qubit

\[ C' = |0\rangle_c \langle 0 | \otimes 1 + |1\rangle_c \langle 1 | \otimes \exp(i\phi\sigma_z^{(1)}) \]

\[ U^{(c)}_{\pi/2} \quad G \quad (U^{(c)}_{\pi/2})^{-1} \]

\[ |0\rangle \quad |\Psi\rangle \quad |A\rangle |B\rangle \quad |+\rangle \quad |1\rangle \quad |0\rangle \quad |-\rangle \quad |4\rangle \quad |2\rangle \quad |+\rangle \quad |3\rangle \quad X\text{-controller} \]
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undo the mapping step
2. Dissipative Step

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Hilbert space of the four spins

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\[ U_{\pi/2}^{(c)} \quad G \quad (U_{\pi/2}^{(c)})^{-1} \]

dissipative step: optical pumping of the control atom

undo the mapping step
2. Dissipative Step

- map the eigenvalue information onto the controller
  \[ S_x |\Psi\rangle = +1 |\Psi\rangle \quad S_x |\Psi\rangle = -1 |\Psi\rangle \]
  
  Hilbert space of the four spins
  
  |0\rangle \quad |1\rangle

- conditional spin flip of one qubit
  \[ C' = |0\rangle_c \langle 0 | \otimes 1 + |1\rangle_c \langle 1 | \otimes \exp(i\phi \sigma^{(1)}_z) \]

- dissipative step: optical pumping of the control atom
  \[ U^{(c)}_{\pi/2} \quad G \quad (U^{(c)}_{\pi/2})^{-1} \]

- undo the mapping step
Coherent and Dissipative Time Evolution

We have obtained ...

- Lindblad master equation

\[
\frac{d}{dt} \rho = -i [H, \rho] + \gamma \left( c \rho c \dagger - \frac{1}{2} c \dagger c \rho - \rho \frac{1}{2} c \dagger c \right)
\]

- Coherent evolution: Hamiltonian

\[H = \hbar \sigma_x^{(1)} \sigma_x^{(2)} \sigma_x^{(3)} \sigma_x^{(4)} \quad (\hbar = -\frac{\alpha}{\tau})\]

- Dissipative evolution: quantum jump operator

\[c = \sqrt{\gamma} \sigma_z^{(1)} \left( 1 - \sigma_x^{(1)} \sigma_x^{(2)} \sigma_x^{(3)} \sigma_x^{(4)} \right) \quad (\gamma = \frac{\phi^2}{\tau})\]

- Sweeping over the lattice ...
  - we simulate the toric code Hamiltonian
  - we pump into the ground state
Outlook

- Rydberg quantum simulator

Possible models: Kitaev toric code model, color codes, lattice gauge theories
Hybrid Quantum Systems

- superconducting qubits
- quantum dot spin qubits
- impurities: NV centers etc.
- nuclear spin ensembles
- photons / CQED
  - optical / photonic cavities
  - microwave / sc stripline
- nano-mechanics
  - opto-/electro-
- ...

trademark:  • nanotechnology
           • scalability

... success stories ...

- atoms, ions, molecules
  - single atoms and ensembles
  - trapping and cooling (BEC)
- photons / CQED
  - cavities: optical and microwave
  - free space
- ...

- “ideal” quantum systems
Hybrid Quantum Systems

challenge: “hybrid systems”

- develop coherent quantum interface *between solid state and AMO systems*
  - basic building block
  - goal: combining advantages (benefit from complementary toolboxes) with compatible experimental setups
Hybrid Quantum Systems

example:

solid state quantum processor

AMO memory

read / write via bus

challenge: “hybrid systems”

- hybrid quantum processor
- ...
- solid state traps / elements for AMO physics
  - benefit from nanofabrication / integration (scalability)
  - new physics ...

- nanotraps / scalable
- mediated interactions
Hybrid Quantum Systems

quantum interface - how?

- optical photons
- microwave photons
- direct coupling
- free space / long distance
- cavities
- trapping close to surface, in cryostat?
- deterministic & probabilistic protocols
Hybrid Quantum Systems

quantum interface - how?

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Hybrid Quantum Systems

quantum interface - how?

- optical photons
- microwave photons
- direct coupling
- deterministic & probabilistic protocols

- free space / long distance
- cavities
- trapping close to surface, in cryostat?
Examples:

- Opto-Nanomechanics + Atom(s)
- Circuit QED + Polar Molecules
- CQED: Microtoroids + Atoms (Quantum Networks)
- Nanoscale AMO physics

Caltech + Munich + Innsbruck

Hybrid Quantum Processors

Harvard + Yale + Innsbruck

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Opto-nanomechanics + atom(s)

- QND measurement based EPR entanglement between oscillator + atomic ensembles

K. Hammerer, M. Aspelmeyer, E. Polzik, P. Z., PRL 2009
Opto-nanomechanics + atom(s)

- QND measurement based EPR entanglement between oscillator + atomic ensembles

- Free space coupling between nanomechanical mirror + atomic ensemble

K. Hammerer, M. Aspelmeyer, E. Polzik, P. Z., PRL 2009

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Opto-nanomechanics + atom(s)

- QND measurement based EPR entanglement between oscillator + atomic ensembles

  ![Diagram showing laser, oscillator, EPR, atoms, measurement](image)

  K. Hammerer, M. Aspelmeyer, E. Polzik, P. Z., PRL 2009

- Free space coupling between nanomechanical mirror + atomic ensemble

  ![Diagram showing Cryo, oscillators, atoms, optical lattice, UHV](image)

  Innsbruck + Munich

- … and strong coupling between a *single* atom and a membrane

  ![Diagram showing high-Q cavity, membrane, single atom](image)

  Caltech + Munich + Innsbruck, preprint

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Strong Coupling of Single Trapped Atom to Membrane

- Laser
- Atom trapped in optical lattice
- Moving membrane
- Photons

✓ Cavity mediated: coupling ~ finesse
✓ Coherent coupling >> dissipation


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Strong Coupling of Single Trapped Atom to Membrane
Strong Coupling of Single Trapped Atom to Membrane
Strong Coupling of Single Trapped Atom to Membrane

Cavity response

Frequency

Laser

Membrane
Strong Coupling of Single Trapped Atom to Membrane

- cavity response
- frequency
- laser
- trapped atom
- membrane
Strong Coupling of Single Trapped Atom to Membrane

moving membrane displaces atom trap
coupling $\sim$ finesse
Strong Coupling of Single Trapped Atom to Membrane

- coherent coupling $\gg$ dissipation

\[ H = \omega_m a_m^{\dagger} a_m + \omega_i a_i^{\dagger} a_i + g(a_m^{\dagger} a_a + \text{h.c.)} \]

oscillator atom

- (quantum) noise & imperfections

membrane:
- damping
- temperature
- laser heating

atom + cavity:
- cavity damping
- spontaneous emission
- ...

moving membrane displaces atom trap
coupling $\sim$ finesse
Numbers:

**ADJUSTABLE PARAMETERS**

- **Mechanical frequency:**
  \[ \omega_m/2\pi = 0.78 \text{ MHz} \]

- **Membrane mass:**
  \[ m_m = 1.00 \text{ ng} \]

- **Cavity length:**
  \[ L = 50. \text{ \(\mu\)m} \]

- **Cavity waist:**
  \[ w_0 = 10.00 \text{ \(\mu\)m} \]

- **Detuning from cavity resonance:**
  \[ \Delta = 9.99 \times \kappa_c \]

- **Imbalance in couplings:**
  \[ s = 0.65 = \frac{g_0}{g_0} \]

- **Rotating wave parameter:**
  \[ r = 0.100 = \frac{\lambda}{\omega_m} \]

**FIGURES OF MERIT**

- **Lamb Dicke parameter:**
  \[ \kappa_c \times \text{lat} = 0.051 \]

- **Decoherence due to cavity decay:**
  \[ \frac{\Gamma_c}{\lambda} = 0.055 \]

- **Decoherence due to spontaneous emission:**
  \[ \frac{\Gamma_{at}}{\lambda} = 0.056 \]

- **Decoherence due to thermal heating:**
  \[ \frac{\Gamma_m}{\lambda} = 0.053 \]

- **Circulating power:**
  \[ P_{circ} = 3.94 \text{ mW} \]

- **Sideband parameter:**
  \[ \frac{\kappa_c}{\omega_m} = 19.00 \]

- **Relative shift of lattices:**
  \[ l = 1.60 \text{ nm} \]

**ABSOLUTE NUMBERS**

- **Atom-membrane coupling:**
  
  - Decoherence rate due to cavity decay:
  \[ \Delta_{c} = 4.33 \text{ kHz} \]
  
  - Decoherence rate due to spontaneous emission:
  \[ \Delta_{at} = 4.36 \text{ kHz} \]
  
  - Decoherence rate due to thermal heating:
  \[ \Delta_{m} = 4.17 \text{ kHz} \]

- **Single photon Rabi frequency:**
  \[ \Omega = 553. \text{ kHz} \]

- **Single photon energy shift:**
  \[ \delta = 9.81 \text{ GHz} \]

- **G0/2\pi:**
  \[ \frac{g_0}{2\pi} = 73.7 \text{ MHz} \]

- **Gc/2\pi:**
  \[ \frac{g_c}{2\pi} = 18.5 \text{ kHz} \]

- **U/2\pi:**
  \[ \frac{U}{2\pi} = 553. \text{ kHz} \]

- **\lambda/2\pi:**
  \[ \frac{\lambda}{2\pi} = 78.00 \text{ kHz} \]

K. Hammerer, C. Genes

H. J. Kimble & J. Ye

P. Treutlein
Transfer of a n=1 Fock state: membrane - atom

Wigner function atom

atom initial state n=1

Wigner function membrane

membrane transferred state t=\pi/2G

\[ G=2n*16 \text{ kHz}, \Gamma_\text{at}/G = 10\%, \]
\[ \Gamma_\text{m}/G = 15\%, \]
\[ \Gamma_\text{c}/G = 15\% \]

bad / good \sim 15\%

(present experimental parameters)
Transfer of a n=1 Fock state: membrane - atom

Wigner function atom

atom initial state n=1

Wigner function membrane

membrane transferred state t=\pi/2G

$G=2*\pi*16 \text{ kHz}$, $\Gamma_{at}/G = 5\%$,
$\Gamma_{m}/G = 5\%$,
$\Gamma_{c}/G = 5\%$

bad / good $\sim 5\%$
Transfer of a Squeezed State

Atommembrane

\[ p_{at} \]

\[ p_{m} \]

\[ x_{at} \]

\[ x_{m} \]

\[ t = 0 \quad t \cdot G = \frac{\pi}{2} \quad t \cdot G = \pi \]

time

bad / good ~ 10%

squeezed state

thermal state

~ 30%
Conclusions and Outlook

- develop coherent quantum interface between solid state and AMO systems
  - basic building block
  - goal: combining advantages (benefit from complementary toolboxes) with compatible experimental setups

- hybrid quantum processor
- AMO based preparation / measurement / sensors
- solid state traps / elements for AMO physics
  - benefit from nanofabrication / integration (scalability)
  - new physics ...
Traps for AMO:
… integration of AMO with on-chip devices
… towards AMO physics on the nanoscale
Scalable Ion Trap Quantum Computing

- **present approach**: physically transporting qubit

ion trap quantum computer

idea: Wineland et al.
exp.: Innsbruck, NIST Boulder, JQI, Oxford,...
cryogenic traps: MIT

R. Slusher, Georgia Tech
(also: C. Monroe & K. Schwab)

50 μm scale
Scalable Ion Trap Quantum Computing

- **present approach:** physically transporting qubit

ion trap quantum computer

- **hybrid**

  e.g. wire

  connecting two quantum optical qubits by a (passive) solid state bus

  interfacing active devices

  theory: L. Tian et al.

  exp.: H. Häffner & R. Blatt / Walraff

  compare: polar molecule / Rydberg

idea: Wineland et al.

exp.: Innsbruck, NIST

Boulder, JQI, Oxford,...

cryogenic traps: MIT
Towards AMO physics on the nanoscale

• Tightly confined radiation for trapping, cooling of isolated atoms
• Example: dipole traps & optical lattices using plasmons

1. sharp, conducting nanotip illuminated by light: “lightning rod” effect = trap
2. coupling to plasmon modes = read out, (and interactions)
3. surface effects: Van der Waals and “polarization noise”

- Tight atom confinement, large energy scales
- Strong blue “shield” for nanotip:
  for suspended wires van der Waals significant only @ distances < wire size

D.Chang et al., Park / PZ / M Lukin, in preparation
See also: nano-particle plasmon tweezer @ICFO (Barcelona), atoms around nanotubes ideas (Hau)
Towards AMO physics on the nanoscale

- Tightly confined radiation for trapping, cooling of isolated atoms
- Example: dipole traps & optical lattices using plasmons

- silver nanotip and sodium atoms
  - Distance from trap $z_{\text{trap}} = 30\,\text{nm}$
  - Effective cooperativity $C \sim 4$

- trap frequency
  - $\sim 100$ MHz (4 nm ground state)
- spin flip rate
  - $\sim 1$ ms
- trap life time
  - $\sim 40$ ms (extend with sideband cooling?)

D. Chang
Potential Applications of Nanoscale Traps

- Nonlinear optics: single photon switches and transistors

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- Nonlinear optics: single photon switches and transistors


- Single atom positioning and control for CQED
Potential Applications of Nanoscale Traps

• Nonlinear optics: single photon switches and transistors


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• Scanning sensors based on single atoms
Potential Applications of Nanoscale Traps

- Nonlinear optics: single photon switches and transistors
  

- Single atom positioning and control for CQED

- Scanning sensors based on single atoms

- Lattices with sub-wavelength control (e.g. quantum simulation)