Quantum Computing with neutral atoms and artificial ions

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Outline

• [Quantum Computing based on] neutral atoms in optical lattices
  – spin-dependent lattices
  – high fidelity loading of large lattice arrays beyond Mott insulator

• Entangling atoms
  – two-atoms Feshbach & photoassociation gates
  – atoms in pipeline structures

• All-optical quantum computing with quantum dots
  – Suppressing decoherence via quantum-optical techniques

experiments by I. Bloch et al., LMU & NIST Gaithersburg
Rabl et al.
Dorner et al.
Background: atoms in spin-dependent optical lattices

- optical lattice: spatially varying AC Stark shifts by interfering laser beams
- trapping potential depends on the internal state

- we can move one potential relative to the other, and thus transport the component in one internal state
interactions by moving the lattice + colliding the atoms “by hand”

Ising type interaction: building block of the Universal Quantum Simulator

\[ H : \frac{J}{2} \geq \hat{q}_{\alpha,\beta} \hat{a} \hat{a}^{\dagger} \hat{b}^{\dagger} \hat{b} \]

nearest neighbor, next to nearest neighbor ....
Correcting defects in optical lattices

- Preparation of qubits via a superfluid – Mott insulator phase transition
- Mott insulator have still some defects ...
  present LMU exp.: approx. 1 out of 10 (not optimized)

Questions:
- Even “more regular” loading?
- Can we heal defects?
- Self-healing?

Rem: it seems difficult to do this in normal solids
Defect free optical crystals (for quantum computing)

prepare a Mott insulator with $n=2$ atoms:

\[
\begin{align*}
|\text{a}\rangle & \quad \text{defect: 1 atom} \\
|\text{b}\rangle & \quad \text{defect: 3 atoms}
\end{align*}
\]

After detuning sweep: exactly one atom in b

\[
\begin{align*}
|1, 0\rangle & \rightarrow |0, 1\rangle \\
|2, 0\rangle & \rightarrow |1, 1\rangle \\
|3, 0\rangle & \rightarrow |2, 1\rangle
\end{align*}
\]

\[
\begin{align*}
|0, 1\rangle & \quad \text{1 atom} \\
|1, 0\rangle & \\
|0, 2\rangle & \quad \text{2 atoms} \\
|1, 1\rangle \\
|2, 0\rangle \\
|0, 3\rangle & \quad \text{3 atoms} \\
|1, 2\rangle \\
|2, 1\rangle \\
|3, 0\rangle
\end{align*}
\]

\[\begin{align*}
\Phi & = U_{aa} \\
\delta & = U_{bb}
\end{align*}\]
Collision gates & speed

- validity of the Hubbard model

\[ \frac{4Za_s}{m} \frac{2}{Xd^3x} \left| \psi \right|^4 \text{, } T \]

we can tune to a resonance to have a (free space) scattering length

\[ a_s \quad a_0 \]

\[ ^{87}\text{Rb scattering length (E/k_B=1 nK) for a + a collisions} \]
$\left[ ? \frac{2}{2mR^2} + \frac{1}{2} \gamma m \vec{p}^2 \right] b_{cm} \vec{r} \hat{p} : E_{cm} b_{cm} \vec{r} \hat{p}$

$\left[ ? \frac{2}{2m} \vec{r}^2 + \frac{1}{2} ST^2 r^2 + V \hat{r} \hat{p} \right] b \vec{r} \hat{p} : E \hat{b} \vec{r} \hat{p}$

Born Oppenheimer potentials including trap

harmonic approximation

photoassociation resonance

$\frac{1}{2} ST^2 r^2$

$v = 0, 1, 2, 3$

(schematic not to scale)

$\frac{C_6}{r^6}$

$D_e ; 10^{12} \text{ Hz}$

$<5 \text{ nm}$
Coupling into molecular states via a "Feshbach ramp"

$^{87}\text{Rb} 100 \text{ kHz trap, 6-level model}$

$100.7 \text{ mT aa Resonance, } \Delta_n = 0.017 \text{ mT, } s_n = 38 \text{ MHz/mT, } A_{bg} = 5.29 \text{ nm}$

FIG. 7. Diabatic and adiabatic energy levels of a double Feshbach ramp. The bare resonance energy is held at a constant value between times $t \omega_h$ of 25 and 35, then ramped back across threshold with a ramp functions that is the inverse of the first one.
Feshbach switching in a spherical trap

- Start with the Feshbach resonance state 10 trap units above threshold
- Switch it suddenly close to threshold
- Wait ~ 1 trap time (~µs assuming MHz trap)
- Switch back
- A phase $\pi$ is accumulated
- Fidelity: 0.9996

- No state dependence required, however difficult atom separation with state-independent potential

- State dependence: lattice displacement
- Non-adiabatic transport in optical lattice: simulation with realistic potential shape
- Fidelity 0.99999 in 1.5 trap times through optimal control theory
Feshbach ramp in an elongated trap

- Assumptions:
  - Cigar-shaped trap
  - Transverse motion “frozen”
- Lower longitudinal density of states
  - Bigger coupling to each level
  - Smaller non-adiabatic crossing
- Smoothly varying magnetic field
- Phase gate in 1 trap time with fidelity 0.9996
- Disadvantage: quasi-1D requirement limits trap frequency & speed

- Idea: use this in a “free-fall” scheme where no state-dependent potential would be needed
Alternative trap designs

- pattern loading, e.g. for addressing single atoms

- Microlens arrays
Atom chips

- magnetic traps

issues:
- conservative potential surface effects
- single atom loading
- laser cooling
- loading from a BEC Mott insulator loading?

Atom (qubit) transport loading

micro trap

control pad for selective addressing of each sub system

reservoir (BEC)

processing in arrays of micro traps

light for processing

detector

Heidelberg, Munich, Harvard, Orsay
Optical-tweezers double trap for two single atoms

- A single atom is trapped in each site

Resolution of the imaging system: one micron per pixel

N. Schlosser et al, Nature 411, 1024 (2001)

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Atoms in 1D pipelines

• beamsplitter

• motivation: 1D experiments with optical (and magnetic) traps
Atoms in 1D lattices

Beam splitter

1 atom per site

Atoms in a longitudinal lattice are moved across a beam splitter.

Splitter increases “spatial separation” of the wells in an adiabatic way.

Transverse potential at a lattice site

Tunneling
Atoms in 1D lattices

Beam splitter: attractive or repulsive interaction between adjacent atoms

\[(\alpha |\bullet\rangle + \beta |\circ\rangle)^\otimes N\]

product state

attractive

\[\alpha |\bullet\rangle|\bullet\rangle + \beta |\circ\rangle|\circ\rangle\]

max entangled state

repulsive

\[\alpha |\circ\rangle|\bullet\rangle + \beta |\bullet\rangle|\circ\rangle\]

max entangled state

Nearest neighbor interaction: cold collisions, dipole-dipole (Rydberg atoms)
Atoms in 1D lattices

Motivations:

- Interferometry (attractive interaction)

\[
(\alpha |\bullet\rangle + \beta |\bigcirc\rangle)^\otimes N \quad \Rightarrow \quad \alpha |\bullet\bullet\bullet\rangle + \beta |\bigcirc\rangle
\]

very sensitive to (global) unbalance

\[
\alpha |\bullet\bullet\bullet\rangle + \beta e^{iN\phi} |\bigcirc\bullet\bullet\rangle
\]

- Store qubit in a protected quantum memory (repulsive interaction)

\[
\alpha |\bullet\bullet\rangle + \beta |\bullet\bullet\rangle
\]

unbalance:

insensitive to (global) unbalance
Identifying the ground states as qubits:

\[
|0\rangle = |\downarrow\uparrow\ldots\downarrow\uparrow\rangle \\
|1\rangle = |\uparrow\downarrow\ldots\uparrow\downarrow\rangle
\]

\( J_x = 0 \): Two degenerate ground states form a protected quantum memory

- Separated by a gap 2W from the higher excited states
- Insensitive to global fluctuations of the form

\[
\sum_{l=1}^{N} \sigma_{l}^{x,y,z}
\]

(insensitive to fluctuations in unbalance, fluctuations in tunneling barrier)
Two qubit gates

\[ W' \]

Interaction \( W' \) leads to state selective time evolution

Truth table:

\[
\begin{align*}
|0\rangle|0\rangle & \rightarrow |0\rangle|0\rangle \\
|1\rangle|1\rangle & \rightarrow |1\rangle|1\rangle \\
|0\rangle|1\rangle & \rightarrow e^{-i\phi} |0\rangle|1\rangle \\
|1\rangle|0\rangle & \rightarrow e^{-i\phi} |1\rangle|0\rangle \\
\end{align*}
\]

Collectively enhanced phase:

\[ \phi = NW'\tau/2 \]
All-optical spin quantum gates in quantum dots

• QIP: solid state implementation
  + scalable, fast
  + in line with present nanostructure developments
  - decoherence
• ... coming from quantum optics
  – quantum dots are like artificial atoms: „engineering“ atomic structure
  – spin-based optical quantum gates in semiconductor quantum dots
• ideas from quantum optics may help in suppressing decoherence
Coupling spin to charge via Pauli blocking

$| x^- \rangle \equiv c^{\dagger}_{0,1/2} c^{\dagger}_{0,-1/2} d^{\dagger}_{0,3/2} | \text{vac} \rangle$

Idealized model: three-level system

$| 0 \rangle \equiv c^{\dagger}_{0,-1/2} | \text{vac} \rangle$

$| 1 \rangle \equiv c^{\dagger}_{0,+1/2} | \text{vac} \rangle$

$\sigma^+ : \alpha | 0 \rangle + \beta | 1 \rangle \rightarrow \alpha | 0 \rangle + \beta | x^- \rangle$
Selective phase via bi-excitonic interaction

- Laser addressing
- Exciton couples only to state $|1\rangle$
- External electric field displaces electrons and holes
- Dipole-dipole interaction induces logical phase

\[
\begin{align*}
|0\rangle_a |0\rangle_b & \quad \bullet \quad \_ \quad \_ \quad \bullet \quad \_ \quad \_ \\
|1\rangle_a |0\rangle_b & \quad \bullet \quad \_ \quad \_ \\
|0\rangle_a |1\rangle_b & \quad \_ \quad \_ \quad \_ \quad \bullet \quad \_ \quad \_ \\
|1\rangle_a |1\rangle_b & \quad \_ \quad \_ \quad \_ \quad \_ \quad \_ \quad \_ \\
\end{align*}
\]

\[
\begin{align*}
|0\rangle |0\rangle & \rightarrow |0\rangle |0\rangle \\
|0\rangle |1\rangle & \rightarrow |0\rangle |1\rangle \\
|1\rangle |0\rangle & \rightarrow |1\rangle |0\rangle \\
|1\rangle |1\rangle & \rightarrow e^{i\Delta E_{ab}t} |1\rangle |1\rangle
\end{align*}
\]
Hole mixing problem

- Light holes couple to electron +1/2 states via $\sigma^+$ light
- Actual hole eigenstates comprise a certain admixture from light holes
- Pauli blocking does not work perfectly
- A $\pi + \pi$ pulse for the transition $|1\rangle - |x\rangle$ will leave behind some excitonic population

- A different gate operation procedure is needed
- Model including hole mixing via effective weak coupling to state $|0\rangle$
- Typical value for $\varepsilon$: $\sim 10\%$
Hole-mixing tolerant laser excitation

\[ H_1 = H_0 + \delta |1\rangle \langle 1| + \frac{\varepsilon \Omega}{2} |0\rangle \langle x| + h.c. \]

- Start far from resonance
- Adiabatically change the detuning towards resonance
- Reach |x\rangle from |1\rangle but not from |0\rangle
- Adiabatically de-excite by returning to the initial situation

\[ \alpha |0\rangle + \beta |1\rangle \rightarrow \alpha |0\rangle + \beta \left( \cos \frac{\theta}{2} |1\rangle - \sin \frac{\theta}{2} |x\rangle \right) \]
Adiabatically suppressing decoherence in gate operation

\[ \Omega(t) = \Omega_0 e^{-\left(t/\tau\right)^2} \]
\[ \Delta(t) = \Delta_\infty \left[ 1 - e^{-\left(t/\tau\right)^2} \right] \]

- \( \Omega_0 = 3 \text{ meV} \)
- \( \tau_\Omega = 10 \text{ ps} \)
- \( \Delta E_{ab} = 2 \text{ meV} \)
- \( \Delta_\infty = 3 \text{ meV} \)
- \( \tau_\Delta = 8.72 \text{ ps} \)

- \( \delta = 0.5 \text{ meV} \)

Residual population in the unwanted excitonic states is smaller than \(10^{-6}\) after gate operation.

- Coupling to phonons induces dephasing:
  - Spin-phonon model

\[ \sum \lambda_{j\mathbf{q}} (b_{j\mathbf{q}} + b_{j\mathbf{q}}^\dagger) |x\rangle \langle x| + \omega_{j\mathbf{q}} (b_{j\mathbf{q}}^\dagger b_{j\mathbf{q}}) \]

Phonon Hamiltonian in dressed-state basis:

\[ H_{ph} = \begin{bmatrix} E_+ + \sum_{\mathbf{q}} \omega(\mathbf{q}) b_{\mathbf{q}}^\dagger b_{\mathbf{q}} + \cos\frac{\theta}{2} \lambda_{\mathbf{q}} (b_{\mathbf{q}}^\dagger + b_{\mathbf{q}}) \\ E_- + \sum_{\mathbf{q}} \omega(\mathbf{q}) b_{\mathbf{q}}^\dagger b_{\mathbf{q}} - \sin\frac{\theta}{2} \lambda_{\mathbf{q}} (b_{\mathbf{q}}^\dagger + b_{\mathbf{q}}) \\ \sin\frac{\theta}{2} \sum_{\mathbf{q}} \lambda_{\mathbf{q}} (b_{\mathbf{q}}^\dagger + b_{\mathbf{q}}) (|+\rangle \langle -| + |-\rangle \langle +|) \end{bmatrix} \]

- The same procedure avoids the effect of both hole mixing and phonon decoherence.
Qubit read-out

\[ P_\varepsilon = \frac{\varepsilon^2(1-\eta)}{\varepsilon^2 + \eta} \left[ 1 - \left( \frac{1-\eta}{1+\varepsilon^2} \right)^{1+\varepsilon^{-2}} \right] \]

level scheme with decay

epsilon probability (~0.2% with 80% counting efficiency and 10% mixing)
Summary

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