Toward Scalable Quantum Information Processing based on ultracold atoms in optical lattices

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Outline

- Scalability of quantum information processing?
- Entangle distant qubits by a flying messenger qubit
- Entanglement of atoms via molecular state

(Technical) challenges:
1. Preparation of 1 atom/site
2. Independent control of two atomic species
3. Precision control of atomic interaction
4. Coherence time in the lattice
Overview: Ultra-cold Atoms in an Optical Lattice

Weak lattice potential: BEC Superfluid

Strong lattice potential: Insulator

Insulator plateau of $^{133}\text{Cs}$ in lattices: arXiv:0904.1532v1
Compressibility \( \kappa \equiv \frac{\partial n}{\partial \mu} = \frac{1}{m\omega^2} \frac{dn}{dr} \) (LDA)
Quantum collision microscopy for scalable information processing

1 Cs/100 sites

1 Li/site

100 qubits in (10 site)$^2$

Atomic wavefunction spread
~ 30nm (Cs)
~ 60nm (Li)

(Lattice spacing d=1000 nm)

Scalability to $N \gg 1$ qubits

Cs can be disentangled from the system in the end, leaving only the Li qubits entangled.

Independent control of two atomic species

Li lattice laser intensity $I_{680\text{nm}}$ (W/cm$^2$)

Cs lattice laser intensity $I_{1064\text{nm}}$ (W/cm$^2$)

Cs scattering limit (heating)

Li scattering limit (heating)

Li tunneling limit (bit diffusion)

Cs tunneling limit (bit diffusion)

region where effect of Li Lattice on Cs atoms Minimized and vice versa

usable region of intensity ratios
Choice of internal states: Lithium and Cesium

$^6\text{Li}$

- $2^2\text{P}_{3/2}$
- $F' = 1/2, 3/2, 5/2$
- $2^2\text{S}_{1/2}$
- $F = 3/2, 1/2$
- $m_f = -3/2, -1/2, 1/2, 3/2$

$671 \text{ nm}$

$^\text{133}\text{Cs}$

- $6^2\text{P}_{3/2}$
- $F' = 5, 4, 3, 2$
- $6^2\text{S}_{1/2}$
- $F = 4, 3$
- $m_f = -4, -3, -2, -1, 0, 1, 2, 3, 4$

- $852 \text{ nm}$

$228 \text{ MHz}$

9.2 GHz

States have same Zeeman shift and so will always shift the same way

‘Clock’ states manetic field insensitive to first order
A Universal Set of Gates: Targeted Single Qubit Rotations

Only atoms that are overlapped will be affected by these laser pulses.

A Universal Set of Gates: Entangling Operations

Above pulses show controlled-NOT gate with Cs as control bit and Li as target bit.

Making Commensurate 2-D Lattices

Lattice spacing independent of wavelength of light!

Optical lattice set-up: Klinger et al. (manuscript in preparation)
Making Commensurate 2-D Lattices

Lattice spacing independent of wavelength of light!

D = 16 microns

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Making Commensurate 2-D Lattices

Lattice spacing independent of wavelength of light!

same lattice constant! d~1.5micron

1064 nm lattice (Cs lattice)
681 nm lattice (Li lattice)

D=16 microns

Optical lattice set-up: Klinger et al. (manuscript in preparation)
Moving the Lattices

Masks for evaporation

Crystal with evaporated silver
Moving the Lattices

Crystal with evaporated silver

Masks for evaporation

(V = 3.4kV applied to one pad)
Summary

Experiment:

Preparation of Mott insulating domain with $\sim 1.0$ atom/site

Simultaneous cooling of both Li and Cs atoms

Construction of ultrastable and translatable two-color optical lattices

Future

Fermionic insulator (qubits) with $1.0000$ Li atom/site

Single site addressing using messenger Cs atoms

Entanglement of atoms via molecular states

Scalability
The University of Chicago
Ultracold Atoms and molecules Group

http://ultracold.uchicago.edu/homepage

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