Towards scalable circuit model quantum computing with neutral atom qubits

M. Saffman
Challenges of Quantum Computing

- Qubit isolation from the environment to preserve quantum states
- High fidelity quantum logic gates
- Qubit measurement without Xtalk
- Quantum error correction costs X10 to X1000 qubit overhead

Leading approaches:
- Trapped ions
- Neutral atoms
- Superconductors
- 2D quantum dots
Dichotomy of Quantum Computing

need full control
strong coupling

weak coupling
to environment

need coupling
for QEC
Neutral atom qubits

\begin{equation}
|1\rangle \quad \tau=34 \text{ years (300 K bath)}
\end{equation}

\begin{equation}
|0\rangle \quad m=0
\end{equation}

\begin{equation}
\nu_0=9,192,631,770 \text{ Hz}
\end{equation}

Quadratic Zeeman: 
\begin{equation}
\nu = \nu_0 + 8.55 \times 10^{10} B_0 \delta B \text{ Hz/T}
\end{equation}

\begin{align*}
B_0 &= 10^{-4} \text{ T, } \\
\delta B &= 10^{-8} \text{ T}
\end{align*}

\begin{equation}
\Delta \nu \sim 0.1 \text{ Hz}
\end{equation}
Neutral atom qubits

\[ \text{Cs 6s}_{1/2} \]

\[ f=3 \quad |0> \quad m=0 \]

\[ f=4 \quad |1> \quad \tau=34 \text{ years} \]

Tensor polarizability & hyperpolarizability

\[ \delta v \sim \alpha I + \beta I^2 \]

Adding sidebands to trap light can make traps doubly magic.

A. Carr & MS, PRL 117, 150801 (2016)
Neutral atom qubits

Coherence times as high as 10 sec. have been measured in optically trapped qubit arrays.

(Dave Weiss, PSU)

Optical Trap

$\text{Cs } 6s_{1/2}$

| $f=4$ | $|1\rangle$ | $f=3$ | $|0\rangle$ | $m=0$ |

Decoherence rate $\sim 0.1$ s$^{-1}$
Neutral atom approach

Rydberg Atoms
Cs 100s

Strong interaction
3 GHz @ 3 μm

12 orders of magnitude!

Hyperfine clock qubits

Weak interaction
0.001 Hz @ 3 μm

Rydberg lifetime
0.3 ms
E field sensitivity

Long coherence
~ 10 s

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Atoms
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Atomic qubits in optical lattices & Rydberg interactions

1D
- New Mexico, Wuhan: 2 sites
- Harvard: 100 sites, atom rearrangement

2D
- ~100 sites, 2D array, red detuned
- 100 sites, 2D array, red detuned
- 49 sites, 2D array, blue detuned
- Max Planck, Garching
- Institut d’Optique
- Wisconsin

3D
- 125 sites, blue detuned
- PSU – not yet Rydberg
Lattice design

2D array of 3D optical traps

Gaussian beam array

121 site array in progress

line array - twice more efficient use of optical power

insensitive to optical perturbations

PRA 88, 013420 (2013)
Rydberg trapping

Blue detuned light traps ground and Rydberg states at intensity minimum.

Accounting for spontaneous lifetime & blackbody repopulation this implies a mechanical trap lifetime.

\[ \tau_{\text{mech}} = 0.35 \text{ ms} \gg \tau_{\text{spont}} \]
Single qubit gates - global

Cs clock state qubits

Bias field of 1.5 G

Microwaves 10 kHz Rabi frequency

9.2 GHz
Randomized benchmarking

Quantify gate fidelity with random sequence of Clifford gates

Fidelity ~ 0.999
Close to threshold for quantum error correction

\[
\begin{align*}
\langle F^2 \rangle_{47 \text{ sites}} & = 0.9983 \pm 0.0014 \\
F^2_{\min} & = 0.9939 \pm 0.0007 \\
F^2_{\max} & = 0.9999 \pm 0.0003
\end{align*}
\]

\[
\begin{align*}
P_{(0)} & = \frac{1}{2} + \frac{1}{2} (1 - d_{1f})(1 - d) \\
F(\rho, \rho') & = \text{Tr} \left[ \sqrt{\sqrt{\rho} \rho' \sqrt{\rho}} \right] \\
F^2 & = 1 - \frac{d}{2}
\end{align*}
\]
Single qubit gates – site selected

Stark shift target site with 2D acousto-optic scanner

Microwave + Stark shift laser
Single qubit gates – multiple sites 2D

Sequential addressing

Switching time < 1 μs

Crosstalk is accumulated in all 7 rotations ~ few %.

Fidelity ~ 0.99   \langle \text{Xtalk} \rangle ~ 0.01
Scalable error correction requires parallel gate operations.

Crossed AOMs access one site at a time.

Row parallel single site gates with multichannel AO deflector.

N times optical power cost for N sites.

Full parallel operation with spatial light modulator

N^2 times optical power cost for N^2 array.
Rydberg blockade $C_Z$ gate

Ideal $C_Z$ Gate

$\omega_q, B >> \Omega >> 1/\tau_{Ryd}$

$$C_Z = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

CNOT experiment

\[ 82s_{1/2} \]
\[ 7p_{1/2} \]
\[ 6s_{1/2} \]

\[ 1038 \text{ nm} \]
\[ 459 \text{ nm} \]

\[ B(R)/2\pi = 23 \text{ MHz} \]
\[ R = 2d = 7.6 \text{ \mu m} \]
\[ \Omega_{Ry}/2\pi = 0.65 \text{ MHz} \]

PRA 92, 022336 (2015)

Ground-Rydberg Rabi oscillations
CNOT sequence & Bell states

State preparation
F=98%

CNOT truth table
F=82%

Bell state:  F=0.73 +/- 0.05
F=0.79 +/- 0.05  (post selected)

CNOT eye diagram

F limited by SPAM errors, atom motion (Doppler), perturbing fields, laser noise, beam position noise, physics.

PRA 92, 022336 (2015)
Improved CNOT protocols

Pulse shaping

Pulse shaping

Two-atom dark state

- $\text{Two-atom dark state}$

- $|1> \rightarrow |r> \rightarrow |r> |1> \rightarrow 2\pi$

- $1-F<10^{-4}$

- $\text{High-fidelity Rydberg-blockade entangling gate using shaped, analytic pulses}$

- L. S. Theis, F. Motzoi, F. K. Wilhelm, M. Saffman

- $\text{High-fidelity Rydberg quantum gate via a two-atom dark state}$

- David Petrosyan, Felix Motzoi, Mark Saffman, and Klaus Mølmer

- PHYSICAL REVIEW A 94, 032306 (2016)

- PHYSICAL REVIEW A 96, 042306 (2017)
Two qubit gates – Scalability

Dense parallel operations not possible due to long range Rydberg interaction

\[ \frac{1}{R^6} \text{vdW interaction} \]

\[ R/d > 5 \] gives

\[ \text{Xtalk} < 10^{-4} \]
Multi-qubit gates

Can turn a bug into a feature for multi-qubit gate operations. Native $\text{CNOT}^k$ & $C_k\text{NOT}$ gates.

Wisconsin, Aarhus, Innsbruck….
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Today</th>
<th>Near term realism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number qubits</td>
<td>80/121</td>
<td>600/900</td>
</tr>
<tr>
<td></td>
<td></td>
<td>laser&amp;optics upgrade</td>
</tr>
<tr>
<td>Fidelity qubit measurement</td>
<td>0.99@10 msec</td>
<td>&gt;0.99@1 msec</td>
</tr>
<tr>
<td></td>
<td></td>
<td>higher NA lens</td>
</tr>
<tr>
<td>Fidelity one-qubit gate</td>
<td>0.99-0.999@100 μs</td>
<td>&gt;0.999@200 ns</td>
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<tr>
<td>Fidelity two-qubit gate</td>
<td>0.73@3 μs</td>
<td>&gt;0.99@500 ns</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Raman laser, sideband cooling, laser noise reduction</td>
</tr>
</tbody>
</table>
Many proposals for cold atom quantum simulators. Erez Zohar yesterday

Rydberg versions

A quantum annealing architecture with all-to-all connectivity from local interactions

Wolfgang Lechner,1,2* Philipp Hauke,1,2 Peter Zoller1,2


A Rydberg quantum simulator

Hendrik Weimer1, Markus Müller2, Igor Lesanovsky3,3, Peter Zoller7 and Hans Peter Büchler1

A coherent quantum annealer with Rydberg atoms

A.W. Glaetzle1,3,4,*, R.M.W. van Bijnen1,2,*, P. Zoller1,2 & W. Lechner1,2

arXiv:1803.00735 A Quantum N-Queens Solver

Valentin Torggler,1 Philipp Aumann,1 Helmut Ritsch,1 and Wolfgang Lechner1
Neutral atom qubits

Optical wiring

Rydberg interactions for entangling gates

Atom-photon interface for connectivity