BEC research in Durham

1. $^{85}\text{Rb}$ BEC Experiment
BEC with Tunable Interactions

2. Rb-Cs Mixtures
Cs Feshbach Resonance

3. Theory: vortices, solitons, sound

Cornish et al, PRL 85, 1795 (2000)


Parker et al. PRL 90, 220401 (2003).
Parker et al. PRL 92, 160403 (2004).

Staff: Simon Cornish, CSA
Students: Margaret Harris, Malcolm Parks, Patrick Tierney
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Staff: Nick Proukakis, CSA
Students: Nick Parker, Eleni Sakallari (-07/04), Andrew Martin
Finance: EPSRC GR/S78339/01
Neutral atom quantum computing in optical lattices: far red or far blue?

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University of Durham

MESUMA 04

Dresden 2004
Outline

Good things for quantum computing

Scalability (optical lattices)

Low decoherence (large detuning)

Far-red

3D CO$_2$ single-site addressable

State-selective single-atom transport

Collisional gates

Experiment

Switchable interactions

Far-blue

Magic Rydberg lattice
Quantum computing: atoms or ions?

1. **Ions.** (ENS, Caltech, MPQ, Sussex)
   - Single-qubit addressable.
   - Switchable interactions.
   - Scaling to 2(3)D.
   - Low decoherence.

2. **Neutral atoms in optical lattice.**
   - Single-qubit addressable.
     - Patterned loading
     - Cavity QED
     - Microtraps
   - Switchable interactions.
     - Rydberg
   - Scaling to 2(3)D.
   - Low decoherence.


3D CO₂ lattice 10 x 10 x 10 sites

Low decoherence

Photon scattering rate for a trap frequency of 1 MHz

Far blue

\[ \nu_{osc} \propto \sqrt{\frac{U_0}{\lambda}} \]

Blue: less power

Lamb-Dicke

\[ \eta \propto \frac{2\pi a_0}{\lambda} \]
Far infrared: 3D CO\textsubscript{2} lattice


1. 11.8 \mu m lattice constant: single-atom addressable.
2. Similar trap depths for most atoms (molecules).

\[ \theta = \text{atan}(2) \]

\[ P = 80 \text{ W} \]

\[ w_0 = 50 \mu \text{m} \]

\[ \nu_x \sim 100 \text{ kHz} \]

\[ \nu_y \sim 75 \text{ kHz} \]
Single-atom conveyor

Photon scattering rate

'Blue' \[ \frac{1}{4} \frac{\hbar \omega}{U_0} < 10^{-2} \]

'Red'

Spin-dependent lattice


Near-infra-red

Wavelength

Range

8.4 µm
Single-atom cooling and detection

Problems:
- Optical pumping and heating
  - Solid angle 1/100
  - Detect 100 photons (1 ms)
  - Heating 2 mK

C. Monroe, D.M. Meekhof, B.E. King, S.R. Jefferts, W.M. Itano, D.J. Wineland, and P. Gould,
Single-atom addressability

$^{87}\text{Rb}$

Stimulated Raman transitions.

Single-site addressable.

Single-qubit rotations.

State-selective single atom transport.

Single-atom cooling and detection.
State-selective transport

\[ 6p^2 P \quad \text{and} \quad 5s^2 S_{1/2} \]

| \( I = 3/2 \) |
| \(| 1 \rangle \) |
| \(| 0 \rangle \) |

Left circular 421.1 nm selects \(| 0 \rangle \)

Right circular 421.4 nm selects \(| 1 \rangle \)
Collisional gates

\[ |0\rangle \xrightarrow{\text{move}} |0\rangle \quad |0\rangle \xrightarrow{\pi/2} |0\rangle \quad |0\rangle \xrightarrow{\pi/2} |1\rangle \quad |1\rangle \xrightarrow{\text{Collisional phase shift}} |1\rangle \]

\[ |0\rangle \xrightarrow{\pi/2} |0\rangle \quad |1\rangle \xrightarrow{\pi/2} |1\rangle \quad |0\rangle \xrightarrow{\pi/2} |1\rangle \quad |1\rangle \xrightarrow{\pi/2} |0\rangle \]
Magnetically insensitive storage

\[ m_F = \pm 2 \]

Raman selection pulse
+ 790.0 nm move beam

University of Durham
Scalable neutral atom quantum computer

1. Initialisation

Detection is not state specific but transport is!

2. Computation

3. Read-out

$|0\rangle$ detection $|1\rangle$ detection
CO$_2$ trap experiment

Lifetime 6.5 s pressure limited

Trapped Number

Time (s)
Solder seal windows

1. Hard solder: melting point 309 °C
2. Tested to 275 °C.
3. Reusable.
4. Flexibility: high optical quality, any substrate, any coating.
5. ZnSe saving – £750 per window!

Pyramid MOT 10^{-9} Torr

Science MOT 10^{-11} Torr

3D chamber

Large diameter laser beam
An optical lattice with single lattice site optical control for quantum engineering

BEC at one site:
- reservoir for extracting single atoms
3D CO\textsubscript{2} trap collisional gates

**Advantages:** single-site addressable

1. State-selective (site-specific) transport:
   - blue detuning: low scattering
   - high trap frequency
   - faster gates
   - magnetically insensitive storage.

**Disadvantages:** CO\textsubscript{2} laser

1. Collisional interactions: slow (not switchable)
   - motional decoherence.
Rydberg gates

D. Jaksch, J.I. Cirac, P. Zoller, S.L. Rolston, R. Cote, M.D. Lukin,

\[ |V_{dd}| = \frac{d_1 d_2}{4\pi \varepsilon_0 r^3} \propto n^4 \quad \tau \propto \frac{1}{n^3} \]

\(~10\ \mu m~

<table>
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<th>n</th>
<th>(V_{dd}) (kHz)</th>
<th>(\tau) (µs)</th>
<th>(\Gamma) (x 2\pi kHz)</th>
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| \(\lambda\) (µm) | 10.6 | 1.06 |
|\(n\) | 25   | 16   |
|\(I\) (Wcm\(^{-2}\)) | 5x10\(^6\) | 5x10\(^4\) |
|\(\tau\) (µs) | 0.01 | 10   |

R. M. Potvliege, private communication
Low decoherence

Photon scattering rate for a trap frequency of 1 MHz

Far blue

- 7p
- 6p
- 5p

25 s\(^{-1}\) at 790 nm!

0.0002 s\(^{-1}\) at 450 nm!

Nd:YAG

Far red

- 7p
- 6p
- 5p

Rb

CO\(_2\)

0.002 s\(^{-1}\)

\(\frac{1}{4}\frac{\hbar\omega}{U_0} \sim 10^{-2}\)

\(0\)
428 nm

More blue!

Long coherence

488 nm 514 nm

4 s Ramsey fringes!

Magic Rydberg lattice

Rb model potential calculation
R.M. Potvliege and C.S. Adams, preprint

τ_{ion} > τ_{Ryd}

5s

428 nm

3d

10d

13d

1. Doubled 856 nm: 3 orthogonal beam pairs. phase stable

2. Mott insulator

3. Local addressing with a ‘pointer’
   T. Calarco et al. quant-ph/0403197

4. Transfer to expandable lattice + state selective transport to perform read-out

| 0⟩ detection | 1⟩ detection

100 kHz

125 mW in 50 µm

6P 2P

I = 3/2

2P 1/2

2S 1/2

421 nm

428 nm
Conclusions

Optical lattices: scalability

Low decoherence

Far-red

3D CO$_2$ single-site addressable

State-selective single-atom conveyor

Collisional gates

Spatially discriminated parallel read-out

Scalable up to $10^3$ qubits

Experiment

Far-blue

Magic Rydberg lattice

Switchable interactions

Experiment
Acknowledgements

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http://massey.dur.ac.uk/