Ensemble Quantum Computing with Atoms in Optical Lattices

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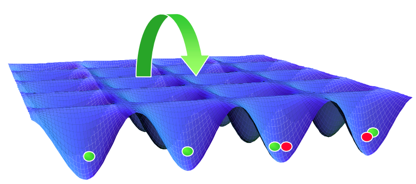
KITP, 11 May 2004

Atoms in optical lattices



POSSIBLE APPLICATIONS:

- Quantum simulations:

- Quantum computations:

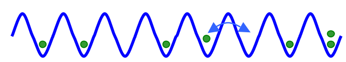
Quantum simulations

Idea (Feynman):

Simulating quantum systems with classical systems is inefficient.

Use a quantum system to simulate other quantum system.

- Atoms in optical (super)lattices:



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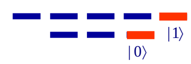
- Using internal levels:



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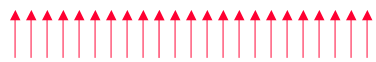
- Magnetic and Electric fields:



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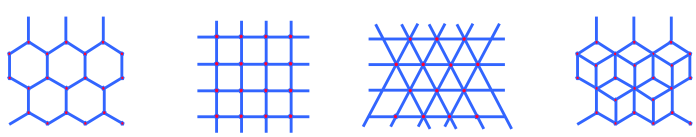
...

Desired Hamiltonian: H

Measure physical properties

Example: Fermions in a 2D lattice

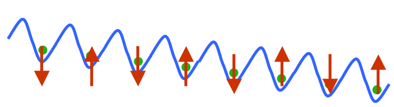
[W. Hofstetter, J.I. Cirac, P. Zoller, E. Demler, and M. Lukin, 2002]



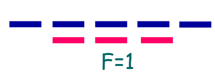
$$H = -t\sum_{k,\sigma} c_{k\sigma}^{\dagger} c_{k\sigma} + V\sum_{k} n_{k\uparrow} n_{k\downarrow}$$

Example: Spin chains and ladders in superlattices.

[J.J. Garcia-Ripoll, M.A. Martin-Delgado and J.I. Cirac, 2004]



$$H = -J\sum_{\alpha,\beta}\left[\vec{S}_{\alpha}\vec{S}_{\beta} + \Delta\left(\vec{S}_{\alpha}\vec{S}_{\beta}\right)^{2}\right] + \sum_{\alpha}(-1)^{\alpha} S_{\alpha}^{z}$$



These systems are interesting in the field of Condensed Matter Physics.

Quantum computations

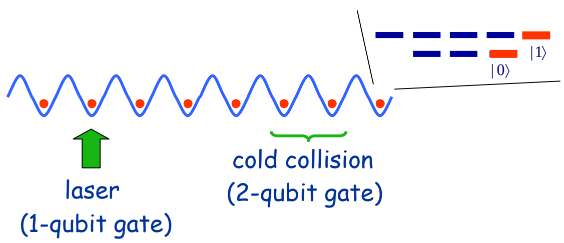
Idea (Deutsch):

Use quantum systems and gates to solve particular problems.

Physical implementation: use atoms in optical lattices

(D. Jaksch, H. Briegel, J.I. Cirac, C. Gardiner, and P. Zoller, 1999)

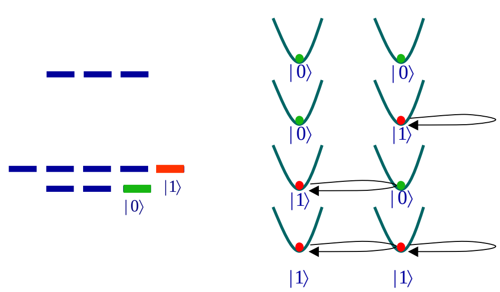
(H. Brennen, I. Deutsch, and C. Caves, 1999)



2-Qubit gate:

(D. Jaksch, H. Briegel, J.I. Cirac, C. Gardiner, and P. Zoller, 1999)

Idea: move atoms until wavefunctions overlap.



Q. Gate

$|00\rangle \leftrightarrow |00\rangle$

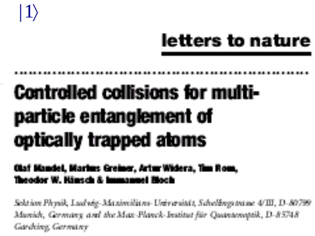
$|01\rangle \leftrightarrow |01\rangle$

$|10\rangle \leftrightarrow -|10\rangle$

$|11\rangle \leftrightarrow |11\rangle$

Experimentally observed!

(I. Bloch and col, 2003)

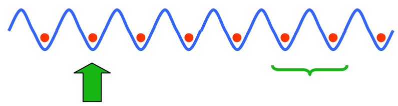

letters to nature

Controlled collisions for multi-particle entanglement of optically trapped atoms

Olaf Mandel, Markus Greiner, Artur Widera, Tim Rom, Theodor W. Hänsch & Immanuel Bloch

Sektion Physik, Ludwig-Maximilians-Universität, Schellingstrasse 4/III, D-80799 Munich, Germany; and the Max-Planck-Institut für Quantenoptik, D-85748 Garching, Germany

Technical Problems



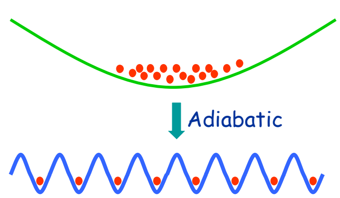
- Laser parameters are not perfectly controlled.
- Scattering properties are not perfectly controlled.
- Random magnetic fields.

  … etc.

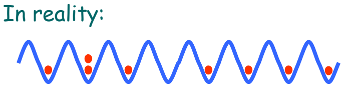
Once a threshold is achieved (□ 10^{-4} error prob./gate) one may use fault tolerant quantum compuation ideas.
(P. Shor, 1996)

(more) Fundamental Problems

1. Presence of defects:



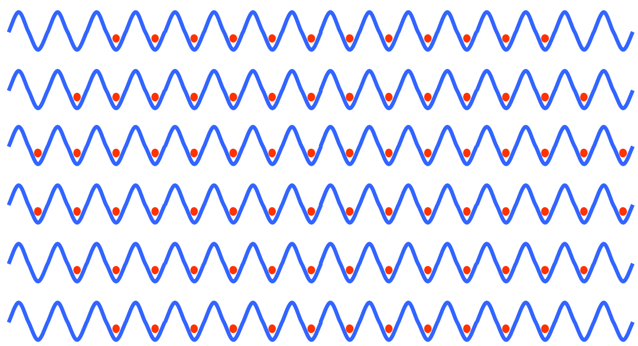
In reality:



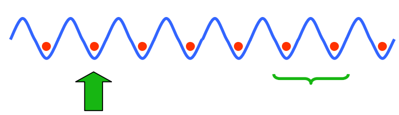
- Atoms/sites not commensurable.
- Temperature is finite.
- Residual potential.

2. Fluctuating atom numbers:

There are many 1D optical lattices in the 3D sample.

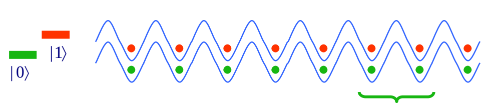


3. Addressability:



- One should focus a laser to about 1 wavelength.

- 2-qubit gates:



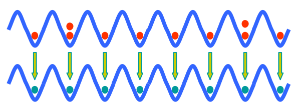
All atoms interact with nearest neighbors at the same time.

Ideas

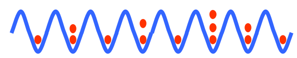
1. Presence of defects:
2. Fluctuating atom numbers:
3. Addressability:

To overcome the presence of defects:

1. Coherently filter the state: (Rabl, Daley, Fedichev, Cirac, and Zoller, 2003)

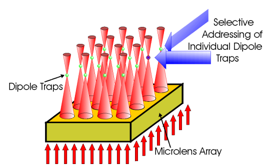


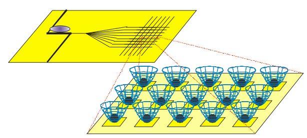
2. Redefine qubits and use new techniques: (Garcia-Ripoll and Cirac, 2003)

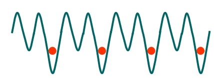


One must avoid defects with no atoms

To acquire addressability: other trap designs







This talk

New schemes fo Quantum Computation

- In the presence of any kind of defects.
- Without knowing the atom number in each lattice.
- Using only global operations (without addressability).

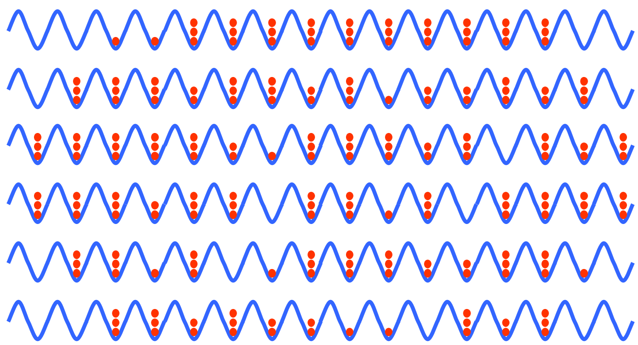
Remarks:

- Use ensembles (several QC distributed randomly across the sample).
- The schemes are scalable.
- They are also useful to initialize the state for a quantum simulation.

Rules of the game

1. Atoms have three internal levels: $|a\rangle, |b\rangle, |p\rangle$

2. Initially, all atoms are in $|a\rangle$, with some given occupation.

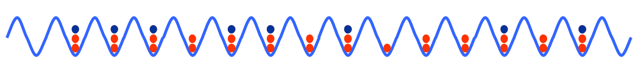


3. The following operations can be applied:

   They are global, i.e. affect to all atoms in the same way.
   (no addressing required)

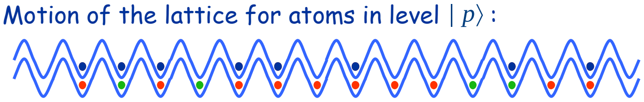
   3.1. Atom transfer from $|a\rangle$ to $|p\rangle : |n,0,0\rangle \leftrightarrow |n-1,0,1\rangle$ with fixed n.

   Example: $|3,0,0\rangle \leftrightarrow |2,0,1\rangle$

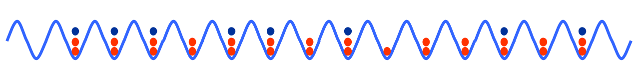


   3.2. Rabi oscillations from $|a\rangle$ to $|b\rangle$:

   3.3. Motion of the lattice for atoms in level $|p\rangle$:



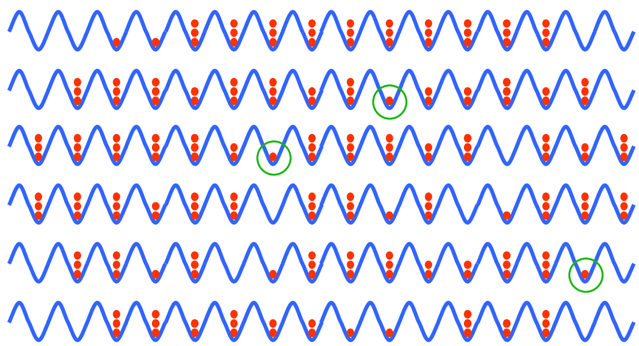
   3.4. Emptying atoms in level $|p\rangle$:



- Use defects, wherever they are, to „mark" pointers.
- Use the pointers to build quantum computers randomly distributed.
- Use the pointers to perform the quantum gates.

ILLUSTRATION:

Pointers: one-atom sites with
- at least 4 sites to their left
- each of them with more than 1 atom.
- no other pointer in the next 4 sites to their right.



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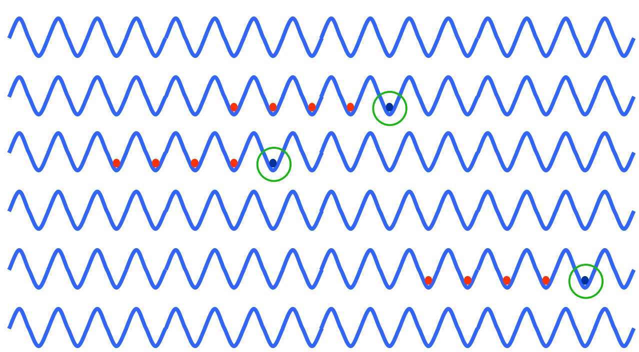
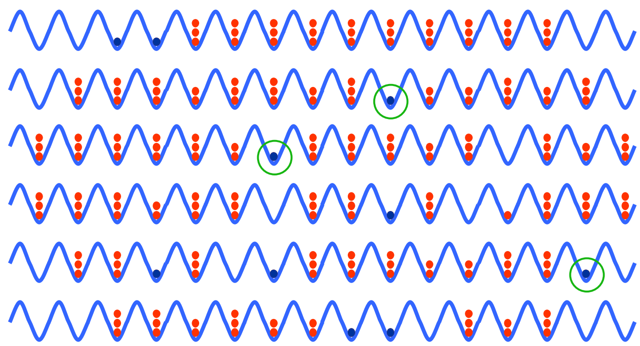


Initialization

STEP 1:
Remove atoms from sites with more than two.

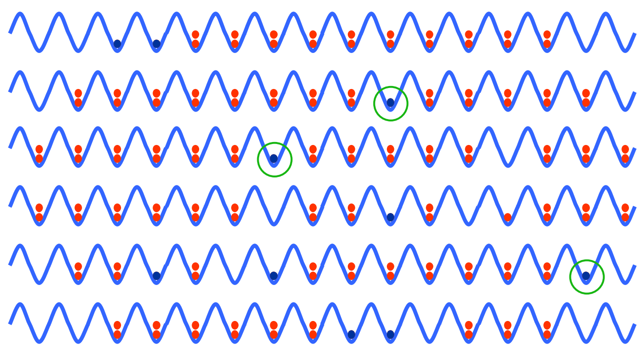
STEP 2:
Transfer all atoms in 1-atom sites to the pointer state $|p\rangle$



Initialization

STEP 3:
Remove one atom in sites next to pointer.

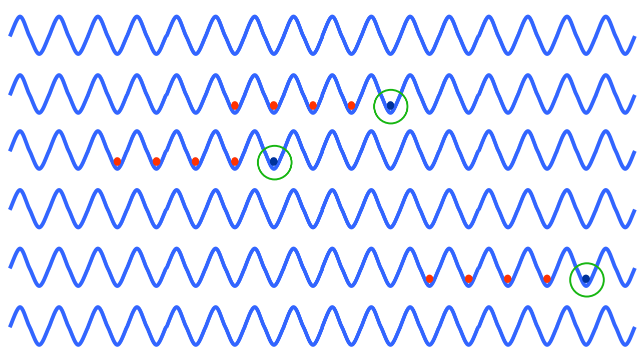
STEP 4:
Remove sites with two atoms.



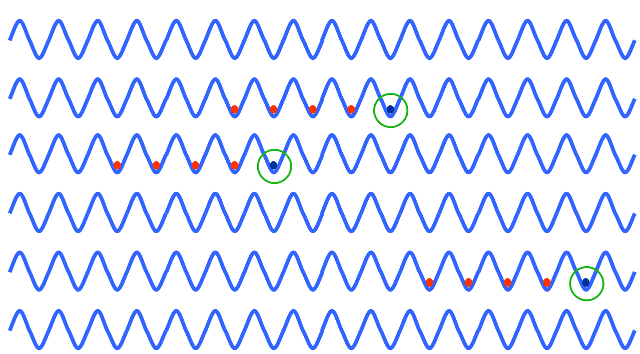
- We end up with:

  - Pointers.
  - Reserved area to their right with four 2-atoms sites.

  The rest of the atoms are removed.

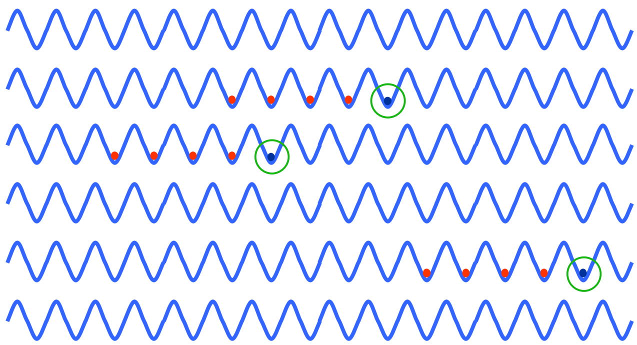


Remarks:



- We are left with a random number of QC at random positions.
- This can also be used to initialize spin chains.
- It also works in 2 and 3 dimensions.

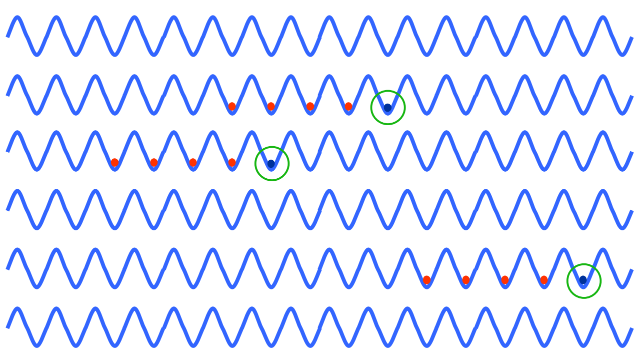
Quantum computing



1-Qubit gates:

- Bring the pointer to the target qubit.
- Apply an operation only if the pointer is present.

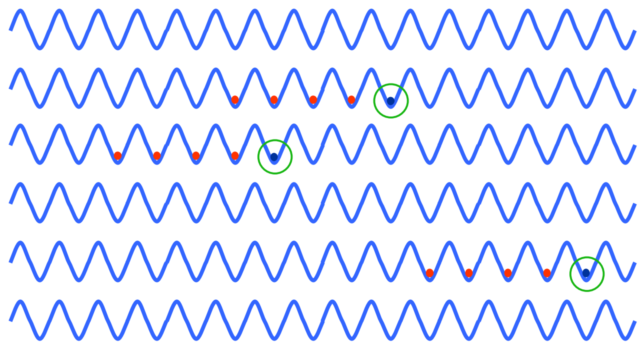
Quantum computing



2-Qubit gates:

- Bring the pointer to the first target qubit.
- Apply an operation only if the pointer is present.
- Bring the pointer to the first target qubit.
- Apply an operation only if the pointer is present.

Quantum computing

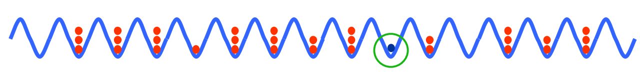


Measurements:

- Bring the pointer to the target qubit.
- Move the pointer to the state $|b\rangle$ if it is empty..
- Detect if there are atoms in the pointer.

Scalability

The probability of having ending up with a quantum computer with N atoms decreases exponentially with N.

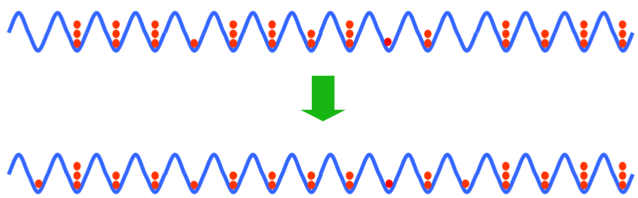


p_n : probability of having n atoms at a given site.

Number of remaining chains: $Np_1(1-p_0-p_1)^N$

Solution: preprocessing

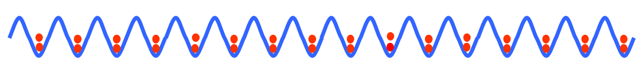
STEP 1: move atoms from heavily populated sites to empty sites.



STEP 2: move atoms from heavily populated sites to 1-atom sites.

- Some atoms must necessarily get lost, in order to decrease entropy.
- Ideally, we end up without defects! We will not have pointer states.

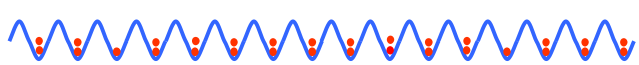
Creating pointer sites



- Apply globally:

$$|a\rangle \rightarrow \sqrt{1-\varepsilon}\,|a\rangle + \sqrt{\varepsilon}\,|p\rangle$$

- Discard atoms in $|p\rangle$:



Adjusting ε we can choose the distribution of defects.

Quantum computing in translationally invariant sytems is possible

Conclusions

- Method to implement a quantum computer in optical lattices:
  - Does not require addressability.
  - Works in the presence of general defects.
  - Number of atoms does not need to be controlled.
  - Uses ensemble quantum computation.
  - Is scalable.
- Once the „technical" aspects can be improved, it can compete with other technologies.
- It can also be used to initialize a quantum simulator.
- From a more fundamental point of view, it shows that quantum computing in a translationally invariant system is possible.