Quantum communication and computation with simple ion traps

Jake Taylor (MIT)
## Motivation

<table>
<thead>
<tr>
<th>Historical</th>
<th>Atomic clocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technological</td>
<td>Precision measurement  &lt;br&gt; Quantum communication  &lt;br&gt; Quantum processors</td>
</tr>
<tr>
<td>Physical</td>
<td>New states of matter?  &lt;br&gt; Quantum simulation?  &lt;br&gt; Nano-scale science?</td>
</tr>
</tbody>
</table>
Architectures

**Qubit shuttle approach**

**Resonator approach**

**Crystal approach**

Distributed computation
Architectures

**Qubit shuttle approach**

**Resonator approach**

**Distributed computation**

**Crystal approach**
Focus of this talk

Quantum communication

Distributed computing

Wigner crystal-based quantum memory
Focus of this talk

Quantum communication

Distributed computing

Wigner crystal-based quantum memory
Small-scale devices

Linear Paul traps + Photons

- good quantum memory
- good local operations
- photons allow quantum communication
Using photons to build entanglement

State-selective transition

(0, 1) Emitter

$(\sqrt{p}|0\rangle + |1\rangle) \otimes (\sqrt{p}|0\rangle + |1\rangle) \rightarrow$
Using photons to build entanglement

State-selective transition
(atom, ion, etc.)

\[ (\sqrt{p}|0\rangle + |1\rangle) \otimes (\sqrt{p}|0\rangle + |1\rangle) \rightarrow \]
Using photons to build entanglement

State-selective transition
(0, 1) (atom, ion, etc.)

\[(\sqrt{p}|0\rangle + |1\rangle) \otimes (\sqrt{p}|0\rangle + |1\rangle) \rightarrow \]

Emitters
Using photons to build entanglement

State-selective transition

(atomic, ion, etc.)

\[(\sqrt{p}|0\rangle + |1\rangle) \otimes (\sqrt{p}|0\rangle + |1\rangle) \rightarrow |1\rangle|1\rangle + \sqrt{p}(|0\rangle|1\rangle + |1\rangle|0\rangle) + O(p)\]
Using photons to build entanglement

State-selective transition

\[ (\sqrt{p}|0\rangle + |1\rangle) \otimes (\sqrt{p}|0\rangle + |1\rangle) \rightarrow \]
\[ |1\rangle |1\rangle + \sqrt{p}(|0\rangle |1\rangle + |1\rangle |0\rangle) + \mathcal{O}(p) \]
Using photons to build entanglement

\[(\sqrt{p}|0\rangle + |1\rangle) \otimes (\sqrt{p}|0\rangle + |1\rangle) \rightarrow |1\rangle |1\rangle + \sqrt{p}(|0\rangle |1\rangle + |1\rangle |0\rangle) + \mathcal{O}(p)\]

State-selective transition
○ (atom, ion, etc.)

Emitter
Using photons to build entanglement

State-selective transition

\( |0\rangle + |1\rangle \otimes |0\rangle + |1\rangle \rightarrow |1\rangle |1\rangle + \sqrt{p}(|0\rangle |1\rangle + |1\rangle |0\rangle) + O(p) \)

Emitter

Memory

State-selective transition

\( |0\rangle, |1\rangle \)

(atomic, ion, etc.)
Using photons to build entanglement

State-selective transition (atom, ion, etc.)

\[ (\sqrt{p}|0\rangle + |1\rangle) \otimes (\sqrt{p}|0\rangle + |1\rangle) \rightarrow |1\rangle|1\rangle + \sqrt{p}(|0\rangle|1\rangle + |1\rangle|0\rangle) + \mathcal{O}(p) \]

- Weak excitation (no two-photon events)
- Single “click” with no which-path information
- Need good memory
Using photons to build entanglement

\[(\sqrt{p}|0\rangle + |1\rangle) \otimes (\sqrt{p}|0\rangle + |1\rangle) \rightarrow |1\rangle |1\rangle + \sqrt{p}(|0\rangle |1\rangle + |1\rangle |0\rangle) + \mathcal{O}(p)\]

- Weak excitation (no two-photon events)
- Single “click” with no which-path information
- Need good memory
Using photons to build entanglement

State-selective transition

(Atom, ion, etc.)

\[ (\sqrt{p}|0\rangle + |1\rangle) \otimes (\sqrt{p}|0\rangle + |1\rangle) \rightarrow |1\rangle |1\rangle + \sqrt{p}(|0\rangle |1\rangle + |1\rangle |0\rangle) + \mathcal{O}(p) \]

- Weak excitation (no two-photon events)
- Single “click” with no which-path information
- Need good memory

Recent experiment! [ Moehring et al., Nature (2007) ]
Using photons to build entanglement

State-selective transition

Q. Communication?
Attenuation problem (exponential with distance)

- Weak excitation (no two-photon events)
- Single “click” with no which-path information
- Need good memory

Recent experiment! [Moehring et al., Nature (2007) ]
Quantum communication: quantum repeaters

[ early ideas: Briegel, Dür, Cirac, Zoller; Bennett, Ekert ]

- Goal: long range entanglement
- Problem: photon attenuation
- Resources: short-range entangled pairs, “local” operations, good quantum memory
Quantum communication: quantum repeaters

[ early ideas: Briegel, Dür, Cirac, Zoller; Bennett, Ekert ]

• Goal: long range entanglement

• Problem: photon attenuation

• Resources: short-range entangled pairs, “local” operations, good quantum memory

• Repeater “node”: a commodity device for quantum communication

• Repeater protocol: divide and conquer
Quantum communication: quantum repeaters

[ early ideas: Briegel, Dür, Cirac, Zoller; Bennett, Ekert ]

• Goal: long range entanglement
• Problem: photon attenuation
• Resources: short-range entangled pairs, “local” operations, good quantum memory

• Repeater “node”: a commodity device for quantum communication
• Repeater protocol: divide and conquer
Quantum communication: quantum repeaters

[ early ideas: Briegel, Dür, Cirac, Zoller; Bennett, Ekert ]

- Goal: long range entanglement
- Problem: photon attenuation
- Resources: short-range entangled pairs, “local” operations, good quantum memory

- Repeater “node”: a commodity device for quantum communication
- Repeater protocol: divide and conquer
Quantum communication: quantum repeaters

[ early ideas: Briegel, Dür, Cirac, Zoller; Bennett, Ekert ]

• Goal: long range entanglement

• Problem: photon attenuation

• Resources: short-range entangled pairs, “local” operations, good quantum memory

• Repeater “node”: a commodity device for quantum communication

• Repeater protocol: divide and conquer
Quantum communication: quantum repeaters

[ early ideas: Briegel, Dür, Cirac, Zoller; Bennett, Ekert ]

• Goal: long range entanglement
• Problem: photon attenuation
• Resources: short-range entangled pairs, “local” operations, good quantum memory
• Repeater “node”: a commodity device for quantum communication
• Repeater protocol: divide and conquer
Quantum communication: quantum repeaters

[ early ideas: Briegel, Dür, Cirac, Zoller; Bennett, Ekert ]

- Goal: long range entanglement
- Problem: photon attenuation
- Resources: short-range entangled pairs, "local" operations, good quantum memory

- Repeater "node": a commodity device for quantum communication
- Repeater protocol: divide and conquer
Quantum repeaters

[ early ideas: Briegel, Dür, Cirac, Zoller; Bennett, Ekert ]

- Goal: long range entanglement
- Problem: photon attenuation
- Resources: short-range entangled pairs, “local” operations, good quantum memory
- Repeater “node”: a commodity device for quantum communication
- Repeater protocol: divide and conquer
Quantum repeaters

- Goal: long range entanglement
- Problem: photon attenuation
- Resources: short-range entangled pairs, “local” operations, good quantum memory
- Repeater “node”: a commodity device for quantum communication
- Repeater protocol: divide and conquer

[ early ideas: Briegel, Dür, Cirac, Zoller; Bennett, Ekert ]
Quantum repeaters

[ early ideas: Briegel, Dür, Cirac, Zoller; Bennett, Ekert ]

- Goal: long range entanglement
- Problem: photon attenuation
- Resources: short-range entangled pairs, “local” operations, good quantum memory

- Repeater “node”: a commodity device for quantum communication
- Repeater protocol: divide and conquer
**Quantum repeaters**

[ early ideas: Briegel, Dür, Cirac, Zoller; Bennett, Ekert ]

- Goal: long range entanglement
- Problem: photon attenuation
- Resources: short-range entangled pairs, “local” operations, good quantum memory

- Repeater “node”: a commodity device for quantum communication
- Repeater protocol: divide and conquer
Quantum repeaters

[ early ideas: Briegel, Dür, Cirac, Zoller; Bennett, Ekert ]

• Goal: long range entanglement

• Problem: photon attenuation

• Resources: short-range entangled pairs, “local” operations, good quantum memory

• Repeater “node”: a commodity device for quantum communication

• Repeater protocol: divide and conquer
Quantum repeaters

[ early ideas: Briegel, Dür, Cirac, Zoller; Bennett, Ekert ]

• Goal: long range entanglement

• Problem: photon attenuation

• Resources: short-range entangled pairs, “local” operations, good quantum memory

• Repeater “node”: a commodity device for quantum communication

• Repeater protocol: divide and conquer
Quantum repeaters

[ early ideas: Briegel, Dür, Cirac, Zoller; Bennett, Ekert ]

- Goal: long range entanglement
- Problem: photon attenuation
- Resources: short-range entangled pairs, “local” operations, good quantum memory
- Repeater “node”: a commodity device for quantum communication
- Repeater protocol: divide and conquer
Quantum repeaters

[ early ideas: Briegel, Dür, Cirac, Zoller; Bennett, Ekert ]

• Goal: long range entanglement
• Problem: photon attenuation
• Resources: short-range entangled pairs, “local” operations, good quantum memory

- Repeater “node”: a commodity device for quantum communication
- Repeater protocol: divide and conquer
Quantum repeaters

[ early ideas: Briegel, Dür, Cirac, Zoller; Bennett, Ekert ]

• Goal: long range entanglement

• Problem: photon attenuation

• Resources: short-range entangled pairs, “local” operations, good quantum memory

• Repeater “node”: a commodity device for quantum communication

• Repeater protocol: divide and conquer
Quantum repeaters

[ early ideas: Briegel, Dür, Cirac, Zoller; Bennett, Ekert ]

- Goal: long range entanglement
- Problem: photon attenuation
- Resources: short-range entangled pairs, “local” operations, good quantum memory

- Repeater “node”: a commodity device for quantum communication
- Repeater protocol: divide and conquer
Quantum repeaters

[ early ideas: Briegel, Dür, Cirac, Zoller; Bennett, Ekert ]

• Goal: long range entanglement
• Problem: photon attenuation
• Resources: short-range entangled pairs, “local” operations, good quantum memory

- Repeater “node”: a commodity device for quantum communication
- Repeater protocol: divide and conquer
Quantum repeaters

[ early ideas: Briegel, Dür, Cirac, Zoller; Bennett, Ekert ]

- Goal: long range entanglement
- Problem: photon attenuation
- Resources: short-range entangled pairs, “local” operations, good quantum memory

Repeaters “node”: a commodity device for quantum communication

Repeater protocol: divide and conquer
Quantum repeaters

- Goal: long range entanglement
- Problem: photon attenuation
- Resources: short-range entangled pairs, “local” operations, good quantum memory
- Repeater “node”: a commodity device for quantum communication
- Repeater protocol: divide and conquer

[ early ideas: Briegel, Dür, Cirac, Zoller; Bennett, Ekert ]
**Quantum repeaters**

[ early ideas: Briegel, Dür, Cirac, Zoller; Bennett, Ekert ]

- Goal: long range entanglement
- Problem: photon attenuation
- Resources: short-range entangled pairs, “local” operations, good quantum memory

- Repeater “node”: a commodity device for quantum communication
- Repeater protocol: divide and conquer

\[ t_{n+1} \sim \frac{4t_n}{p_n p'_{n'}} \]
Quantum repeaters

[ early ideas: Briegel, Dür, Cirac, Zoller; Bennett, Ekert ]

- Goal: long range entanglement
- Problem: photon attenuation
- Resources: short-range entangled pairs, “local” operations, good quantum memory
- Repeater “node”: a commodity device for quantum communication
- Repeater protocol: divide and conquer
  \[ t_{n+1} \sim \frac{4t_n}{p_n p_{n'}} \]
  \[ t_n \sim t_0 \left(\frac{4}{p_n p_{n'}}\right)^n \sim t_0 \ O(\text{poly } d) \]
Quantum repeaters

[ early ideas: Briegel, Dür, Cirac, Zoller; Bennett, Ekert ]

• Goal: long range entanglement
• Problem: photon attenuation
• Resources: short-range entangled pairs, “local” operations, good quantum memory
• Repeater “node”: a commodity device for quantum communication
• Repeater protocol: divide and conquer

\[ t_{n+1} \sim \frac{4t_n}{p_np_n'} \]
\[ t_n \sim t_0 \left(\frac{4}{p_np_n'}\right)^n \sim t_0 \, O(poly \, d) \]

Linear Paul traps + cavities provide good implementation
Minimal-resource repeaters

- Add purification (remove errors):
  need log(d) qubits per node?
**Minimal-resource repeaters**

- Add purification (remove errors): need log(d) qubits per node?

- Sufficient: two qubits

  [ Childress, JMT, Sørensen, Lukin, PRL (2006) ]

- Trade qubits per node for time scaling

- Is there an optimum approach for given resources?
Minimal-resource repeaters

- Add purification (remove errors): need log(d) qubits per node?

- Sufficient: two qubits

  [ Childress, JMT, Sørensen, Lukin, PRL (2006) ]

- Trade qubits per node for time scaling

- Is there an optimum approach for given resources?
Minimal-resource repeaters

• Add purification (remove errors): need log(d) qubits per node?

• Sufficient: two qubits

[ Childress, JMT, Sørensen, Lukin, PRL (2006) ]

• Trade qubits per node for time scaling

• Is there an optimum approach for given resources?
Minimal-resource repeaters

• Add purification (remove errors): need $\log(d)$ qubits per node?

• Sufficient: two qubits

[ Childress, JMT, Sørensen, Lukin, PRL (2006) ]

• Trade qubits per node for time scaling

• Is there an optimum approach for given resources?
Minimal-resource repeaters

- Add purification (remove errors): need $\log(d)$ qubits per node?
- Sufficient: two qubits
  
  [ Childress, JMT, Sørensen, Lukin, PRL (2006) ]

- Trade qubits per node for time scaling
- Is there an optimum approach for given resources?
  
  [ Jiang, JMT, Khaneja, Lukin, PNAS (2007) ]
Minimal-resource repeaters

- Add purification (remove errors): need $\log(d)$ qubits per node?

- Sufficient: two qubits

  [ Childress, JMT, Sørensen, Lukin, PRL (2006) ]

- Trade qubits per node for time scaling

- Is there an optimum approach for given resources?

  [ Jiang, JMT, Khaneja, Lukin, PNAS (2007) ]
Minimal-resource repeaters

• Add purification (remove errors): need $\log(d)$ qubits per node?

• Sufficient: two qubits

  [ Childress, JMT, Sørensen, Lukin, PRL (2006) ]

• Trade qubits per node for time scaling

• Is there an optimum approach for given resources?

  [ Jiang, JMT, Khaneja, Lukin, PNAS (2007) ]
### Minimal-resource repeaters

- Add purification (remove errors): need log(d) qubits per node?
- Sufficient: two qubits

  [ Childress, JMT, Sørensen, Lukin, PRL (2006) ]

- Trade qubits per node for time scaling

- Is there an optimum approach for given resources?

  [ Jiang, JMT, Khaneja, Lukin, PNAS (2007) ]
Minimal-resource repeaters

• Add purification (remove errors): need log(d) qubits per node?

• Sufficient: two qubits

  [ Childress, JMT, Sørensen, Lukin, PRL (2006) ]

B-pair

• Trade qubits per node for time scaling

• Is there an optimum approach for given resources?

  [ Jiang, JMT, Khaneja, Lukin, PNAS (2007) ]
• Add purification (remove errors): need log(d) qubits per node?

• Sufficient: two qubits

[ Childress, JMT, Sørensen, Lukin, PRL (2006) ]

• Trade qubits per node for time scaling

• Is there an optimum approach for given resources?

[ Jiang, JMT, Khaneja, Lukin, PNAS (2007) ]
Minimal-resource repeaters

• Add purification (remove errors): need $\log(d)$ qubits per node?

• Sufficient: two qubits

[ Childress, JMT, Sørensen, Lukin, PRL (2006) ]

C-pair

• Trade qubits per node for time scaling

B-pair

• Is there an optimum approach for given resources?

[ Jiang, JMT, Khaneja, Lukin, PNAS (2007) ]
**Minimal-resource repeaters**

- Add purification (remove errors): need $\log(d)$ qubits per node?
- Sufficient: two qubits

  [ Childress, JMT, Sørensen, Lukin, PRL (2006) ]

- Trade qubits per node for time scaling
- Is there an optimum approach for given resources?

  [ Jiang, JMT, Khaneja, Lukin, PNAS (2007) ]
Minimal-resource repeaters

• Add purification (remove errors): need \( \log(d) \) qubits per node?

• Sufficient: two qubits

  [ Childress, JMT, Sørensen, Lukin, PRL (2006) ]

• Trade qubits per node for time scaling

• Is there an optimum approach for given resources?

  [ Jiang, JMT, Khaneja, Lukin, PNAS (2007) ]
Minimal-resource repeaters

- Add purification (remove errors): need log(d) qubits per node?
- Sufficient: two qubits
  
  [ Childress, JMT, Sørensen, Lukin, PRL (2006) ]

Two qubit commodity devices sufficient

- Trade qubits per node for time scaling
- Is there an optimum approach for given resources?

  [ Jiang, JMT, Khaneja, Lukin, PNAS (2007) ]
Focus of this talk

Quantum communication

Distributed computing

Wigner crystal-based quantum memory
Distributed computation

- Problem: apparatus for many qubits?
  - limited coupling strengths in a NMR molecule (frequency selectivity)
  - quantum control in limited space

with L. Jiang, A. Sørensen, M. D. Lukin,
[Harvard, Copenhagen]
Distributed computation

- Problem: apparatus for many qubits?
  - limited coupling strengths in a NMR molecule (frequency selectivity)
  - quantum control in limited space

Experimental realization of Shor's quantum factoring algorithm using nuclear magnetic resonance

Lieven M. K. Vandersypen†, Matthias Steffen‡, Gregory Breyta*, Costantino S. Yannoni†, Mark H. Sherwood* & Isaac L. Chuang†

* IBM Almaden Research Center, San Jose, California 95120, USA
† Solid State and Photonics Laboratory, Stanford University, Stanford, California 94305-4075, USA

The number of steps any classical computer requires in order to find the prime factors of an $l$-digit integer $N$ increases exponentially with $l$, at least using algorithms known at present¹. Factoring large integers is therefore conjectured to be intractable classically, an observation underlying the security of widely used crypto-

with L. Jiang, A. Sørensen, M. D. Lukin, [Harvard, Copenhagen]
Distributed computation

Problem: apparatus for many qubits?
- limited coupling strengths in a NMR molecule (frequency shift)
- quantum computation

Approach: build a **Quantum Register**

Use quantum communication between registers
- noisy, failure prone, still OK

Have good local operation of a given register

Use many local operations to improve (faulty) inter-register operations
Early ideas (monolithic architecture)

A Practical Architecture for Reliable Quantum Computers

Quantum computation has advanced to the point where solutions can help close the gap between emerging quantum and real-world computing requirements.

Mark Oskin
University of Washington

Frederic T. Chong
University of California, Davis

Isaac L. Chuang
Massachusetts Institute of Technology

[ Oskin et al., IEEE 2002 ]
Deterministic distributed computation

desired (logical) circuit
Deterministic distributed computation

desired (logical) circuit

Idea:

- Break into pairwise gates
- Set a “clock cycle” time
  - can have “did not succeed” errors
  - can have logical errors
Deterministic distributed computation

desired (logical) circuit

Idea:
- Break into pairwise gates
- Set a “clock cycle” time
  - can have “did not succeed” errors
  - can have logical errors
Deterministic distributed computation

desired (logical) circuit

Idea:
- Break into pairwise gates
- Set a “clock cycle” time
  - can have “did not succeed” errors
  - can have logical errors

memory
optical
optical
memory
Deterministic distributed computation

desired (logical) circuit

Idea:

• Break into pairwise gates
• Set a “clock cycle” time
  – can have “did not succeed” errors
  – can have logical errors

memory

optical

memory
Deterministic distributed computation

desired (logical) circuit

Idea:
• Break into pairwise gates
• Set a “clock cycle” time
  – can have “did not succeed” errors
  – can have logical errors

memory

optical

memory
Deterministic distributed computation

desired (logical) circuit

Idea:
- Break into pairwise gates
- Set a “clock cycle” time
  - can have “did not succeed” errors
  - can have logical errors
Deterministic distributed computation

desired (logical) circuit

Idea:

• Break into pairwise gates
• Set a “clock cycle” time
  – can have “did not succeed” errors
  – can have logical errors

memory

optical

optical

memory
Deterministic distributed computation

 desired (logical) circuit

Idea:

• Break into pairwise gates
• Set a “clock cycle” time
  – can have “did not succeed” errors
  – can have logical errors
Deterministic distributed computation

desired (logical) circuit

Idea:
• Break into pairwise gates
• Set a “clock cycle” time
  – can have “did not succeed” errors
  – can have logical errors
Deterministic distributed computation

desired (logical) circuit

Idea:
- Break into pairwise gates
- Set a “clock cycle” time
  - can have “did not succeed” errors
  - can have logical errors

memory
optical
 optical
memory

$tc$
Deterministic distributed computation

desired (logical) circuit

Idea:

- Break into pairwise gates
- Set a “clock cycle” time
  - can have “did not succeed” errors
  - can have logical errors

memory
optical
memory

\[
\text{time/gate} = t_c \quad \text{error/gate} = N_{\text{eff}} p_L
\]
A minimal register

Minimum requirements:
- "optical" qubit
  - entanglement generation
  - measurement / initialization
- "memory" qubit
- very good local control
- reasonable optical interface

[ early ideas: Dür & Briegel ]

[ Jiang et al. quant-ph/0703029 ]
A minimal register

Minimum requirements:
- “optical” qubit
  - entanglement generation
  - measurement / initialization
- “memory” qubit
- very good local control
- reasonable optical interface
  [ early ideas: Dür & Briegel ]

[ Jiang et al. quant-ph/0703029 ]
A minimal register

Minimum requirements:
- “optical” qubit
  - entanglement generation
  - measurement / initialization
- “memory” qubit
- very good local control
- reasonable optical interface

Small size ion “computer”
+ Optical interface

Photodetectors & beam splitters

Optical switch

Fiber interconnects

Microwave-/rf-controlled auxillary qubits

Jiang et al. quant-ph/0703029
Dealing with imperfections: 3 more spins

Robust measurement

- imperfect initialization, measurement ($p_L, p_M \sim 5\%$)
- near-perfect local operation ($p_L \sim 0.01\%$)

\[
\tilde{\varepsilon}_M \approx \binom{2m + 1}{m + 1} (p_I + p_M)^{m+1} + (2m + 1) p_L \\
\tilde{t}_M = (2m + 1) (t_I + t_L + t_M)
\]
Dealing with imperfections: 3 more spins

Robust measurement

- imperfect initialization, measurement \((p_I, p_M \sim 5\%)
- near-perfect local operation \((p_L \sim 0.01\%)

\[
\tilde{\varepsilon}_M \approx \left( \frac{2m + 1}{m + 1} \right) (p_I + p_M)^{m+1} + (2m + 1) p_L
\]
\[
\tilde{t}_M = (2m + 1)(t_I + t_L + t_M)
\]

Robust entanglement generation

- Large time overhead \((t_C \sim 100–1000 t_L)
- Initial \(F=0.9\) gives final \(F>0.995\) \((N_{\text{eff}} \sim 20)\)
- Good quantum memory critical

![Graph showing infidelity versus purification steps](image)
Dealing with imperfections: 3 more spins

Robust measurement
- imperfect initialization, measurement (p_l, p_M \sim 5%)
- near-perfect local operation (p_L \sim 0.01%)

Further improvements:
- better collection efficiency via optical cavities (Purcell effect)
  - improves both speed and fidelity

Robust entanglement generation
- Large time overhead
  \((t_C \sim 100–1000 \ t_L)\)
- Initial \(F=0.9\) gives final \(F>0.995\)
  \((N_{\text{eff}} \sim 20)\)
- Good quantum memory \textit{critical}
Dealing with imperfections: 3 more spins

Robust measurement
- imperfect initialization, measurement \((p_I, p_M \sim 5\%)\)
- near-perfect local operation \((p_L \sim 0.01\%)\)

\[
\tilde{\varepsilon}_M \approx \left( \frac{2m + 1}{m + 1} \right) (p_I + p_M)^m \\
\tilde{t}_M = (2m + 1) (t_I + t_L + t_M)
\]

Further improvements:
- better collection efficiency via optical cavities (Purcell effect)
  - improves both speed and fidelity

Robust entanglement generation
- Large time overhead \((t_C \sim 100-1000 \ t_L)\)
- Initial \(F=0.9\) gives final \(F>0.995\)
  \((N_{\text{eff}} \sim 20)\)
- Good choice...

Scalable architecture for few-qubit systems
Focus of this talk

Quantum communication

Distributed computing

Wigner crystal-based quantum memory
Wigner crystal-based quantum memory

Advantages:
• many ions (good memory)
• self-organized, stable
• optically resolved sites

Problems:
• high temperature
• finite size
• low collection efficiency
Wigner crystal-based quantum memory

Progress toward making spin squeezed states with ions in a Penning-Malmberg trap.

N. Shiga, W.M. Itano and J.J. Bollinger
National Institute of Standard and Technology, 325 Broadway, Boulder, CO 80305, USA
e-mail: shiga@boulder.nist.gov

Problems:
- high temperature
- finite size
- low collection efficiency
Wigner crystal-based quantum memory

Progress toward making spin squeezed states with ions in a Penning-Malmberg trap.

N. Shiga, W.M. Itano and J.J. Bollinger
National Institute of Standard and Technology,
325 Broadway, Boulder, CO 80305, USA
e-mail: shiga@boulder.nist.gov

Problems:
- high temperature
- finite size
- low collection efficiency
Quantum gates at high temperature

Push gates
- AC Stark shift -> effective potential
- Different internal states -> different potentials
- Control sign, strength

Be$^+$

$$V = \sum_i (\vec{x}_i \cdot \vec{f}_i(t)) \sigma_i^z$$

[ Porras & Cirac, PRL 2006 ]
Quantum gates at high temperature

Push gates
- AC Stark shift -> effective potential
- Different internal states -> different potentials
- Control sign, strength

\[ V = \sum_i (\vec{x}_i \cdot \vec{f}_i(t)) \sigma_i^z \]
Quantum gates at high temperature

Push gates
- AC Stark shift -> effective potential
- Different internal states -> different potentials
- Control sign, strength

\[ V = \sum_{i} (\vec{x}_i \cdot \vec{f}_i(t)) \sigma_i^z \]

[Porras & Cirac, PRL 2006]
Quantum gates at high temperature

Push gates
- AC Stark shift -> effective potential
- Different internal states -> different potentials
- Control sign, strength

\[ V = \sum_i (\vec{x}_i \cdot \vec{f}_i(t))\sigma_i^z \]
Quantum gates at high temperature

Push gates
- AC Stark shift -> effective potential
- Different internal states -> different potentials
- Control sign, strength

Coulomb interaction -> effective z-z interaction

Requirement: slow w.r.t. phonon modes (but, no gap!)

$V = \sum_i (\vec{x}_i \cdot \vec{f}_i(t)) \sigma_i^z$

[Porras & Cirac, PRL 2006]
Fast carrier-modulated gate

Idea: modulate force fast w.r.t. phonons (fast-kick)

\[ f(t) \rightarrow \cos(\nu t) f(t) \]

[ García-Ripoll et al. PRL 2003 ]

[ Taylor & Calarco (0706.1951) ]
Fast carrier-modulated gate

Idea: modulate force \textit{fast} w.r.t. phonons (fast-kick)

$$f(t) \rightarrow \cos(\nu t) f(t)$$

[ Garcia-Ripoll et al. PRL 2003 ]
Fast carrier-modulated gate

Idea: modulate force fast w.r.t. phonons (fast-kick)

\[ f(t) \rightarrow \cos(\nu t) f(t) \]  

[ García-Ripoll et al. PRL 2003 ]

[ Taylor & Calarco (0706.1951) ]
Fast carrier-modulated gate

Idea: modulate force *fast* w.r.t. phonons (fast-kick)

\[ f(t) \rightarrow \cos(\nu t) f(t) \]

[ García-Ripoll et al. PRL 2003 ]

[ Taylor & Calarco (0706.1951) ]
Fast carrier-modulated gate

Idea: modulate force fast w.r.t. phonons (fast-kick)

\[ f(t) \rightarrow \cos(\nu t) f(t) \]

[ García-Ripoll et al. PRL 2003 ]

Over an oscillation, no phonon evolution (no heating, no entanglement)

[ Taylor & Calarco (0706.1951) ]
Numerical simulations of gates in 2D

High fidelity at high temperatures
(also works in 3D)
Asymmetric protocols for quantum register-based computation

State-selective transition
\( \bullet \) (atom, ion, etc.)

\[
\begin{array}{c}
\uparrow \\
0 \\
\downarrow \\
1
\end{array}
\]

Entanglement generation

[ Taylor & Calarco (0706.1951) ]
Asymmetric protocols for quantum register-based computation

State-selective transition

○ (atom, ion, etc.)

0 1

Entanglement generation

[ Taylor & Calarco (0706.1951) ]
Asymmetric protocols for quantum register-based computation

State-selective transition

\( \bullet \) (atom, ion, etc.)

\[
\begin{array}{c}
0 \\
\downarrow
\end{array}
\]

\[
\begin{array}{c}
1 \\
\uparrow
\end{array}
\]

Entanglement generation

|0\rangle + |1\rangle

[ Taylor & Calarco (0706.1951) ]
Asymmetric protocols for quantum register-based computation

State-selective transition
○ (atom, ion, etc.)

0 1

Entanglement generation

Emitter

|0⟩ + |1⟩

[ Taylor & Calarco (0706.1951) ]
Asymmetric protocols for quantum register-based computation

State-selective transition

\[ \eta' \left( \sqrt{\frac{\eta}{\eta'}} |01\rangle \pm |10\rangle \right) \left( \sqrt{\frac{\eta}{\eta'}} \langle 01 | \pm \langle 10 | \right) + O(\sqrt{\eta'}) |11\rangle\langle 11 | \]

[ Taylor & Calarco (0706.1951) ]
Asymmetric protocols for quantum register-based computation

State-selective transition

(atom, ion, etc.)

0 \quad 1

Entanglement generation

\eta' \left( \sqrt{\frac{\eta}{\eta'}} |01\rangle \pm |10\rangle \right) \left( \sqrt{\frac{\eta}{\eta'}} \langle 01 | \pm \langle 10 | \right) + O(\sqrt{\eta'}) |11\rangle \langle 11 |

Solution: flip bit, try again

[Taylor & Calarco (0706.1951)]
Asymmetric protocols for quantum register-based computation

State-selective transition
(atomic-ion, etc.)

Entanglement

$\eta' \left( \sqrt{\frac{\eta}{\eta'}} \right) |01\rangle$

Solution: flip bit, try again

$|0\rangle + |1\rangle$

$\sqrt{\eta'} |11\rangle|11\rangle$

[ Taylor & Calarco (0706.1951) ]
Asymmetric protocols for quantum register-based computation

State-selective transition
(atoms, ions, etc.)

Entanglement

$\eta' \left( \sqrt{\frac{\eta}{\eta'}} \right) |01\rangle$

Solution: flip bit, try again

Memory (Penning trap)

Processor (Paul trap)

Interconnect (beam splitter + detectors)

$|0\rangle + |1\rangle$

$\langle \sqrt{\eta'} |11\rangle |11\rangle$

[ Taylor & Calarco (0706.1951) ]
Outlook: cluster generation

[ Taylor & Calarco (0706.1951) ]
Outlook: cluster generation

[ Taylor & Calarco (0706.1951) ]
Outlook: cluster generation

Idea: set spot size, sweep rate for links (—) vs (--)
Outlook: cluster generation

Single laser can generate cluster in $O(n)$ time

Idea: set spot size, sweep rate for links (—) vs (--)
Outlook: cluster generation

Idea: set spot size, sweep rate for links (—) vs (--)
Outlook: cluster generation

Idea: set spot size, sweep rate for links (—) vs (--) 

$$\theta(\omega) = \frac{\Omega^4_0}{\omega^2 \Delta^2} \frac{\alpha^4}{\rho^4} \frac{q^2}{\hbar \epsilon_0 \nu}$$

$$\varepsilon = e^{-3/(8\sigma^2)} (11 - \delta \ln(\delta + 1)/\delta$$

Crystal rotation? use time-dependent displacement

[ Taylor & Calarco (0706.1951) ]
Outlook

• Commodity good: cheap, interchangeable, ubiquitous

• Finite size control problem \textit{per register}.
  
  • GRAPE pulses [Khaneja et al.], feedback & filtering, composite pulses, etc.

• Optical or other “distributed qubit” interconnect system can be faulty
  (<50% errors after post-selection sufficient; for <10%, only 5 qubits needed)

• Implementations:
  
  • NEED: few coupled, controllable qubits with very good quantum memory; optical
    (or phononic, or qubit-bus) interconnection possible

• Other aspects:
  
  • Wigner crystals of ions as a quantum “hard drive”? (Many qubits per device)
# Collaborators

## Harvard:

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>T. Calarco</td>
<td></td>
</tr>
<tr>
<td>J. R. Petta</td>
<td>-&gt; Princeton</td>
</tr>
<tr>
<td>D. Reilly</td>
<td></td>
</tr>
<tr>
<td>A. C. Johnson</td>
<td></td>
</tr>
<tr>
<td>E. A. Laird</td>
<td></td>
</tr>
<tr>
<td>A. Yacoby</td>
<td>&lt;- Weizmann</td>
</tr>
<tr>
<td>C. M. Marcus</td>
<td></td>
</tr>
<tr>
<td>H.-A. Engel</td>
<td></td>
</tr>
<tr>
<td>L. Jiang</td>
<td></td>
</tr>
<tr>
<td>L. I. Childress</td>
<td></td>
</tr>
<tr>
<td>M. G. Dutt</td>
<td></td>
</tr>
<tr>
<td>A. S. Zibrov</td>
<td></td>
</tr>
<tr>
<td>M. D. Lukin</td>
<td></td>
</tr>
</tbody>
</table>

## Elsewhere:

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>W. Dür</td>
<td></td>
</tr>
<tr>
<td>P. Zoller</td>
<td>(Innsbruck)</td>
</tr>
<tr>
<td>A. Imamoglu</td>
<td>(ETH Zürich)</td>
</tr>
<tr>
<td>C. Flindt</td>
<td></td>
</tr>
<tr>
<td>A. Sørensen</td>
<td>(NBI Copenhagen)</td>
</tr>
<tr>
<td>F. Jelezko</td>
<td></td>
</tr>
<tr>
<td>J. Wrachtrup</td>
<td>(Stuttgart)</td>
</tr>
<tr>
<td>P. R. Hemmer</td>
<td>(Texas A&amp;M)</td>
</tr>
<tr>
<td>M. P. Hanson</td>
<td></td>
</tr>
<tr>
<td>A. C. Gossard</td>
<td>(UCSB)</td>
</tr>
</tbody>
</table>

### $$ $$: Pappalardo, ARO, DARPA-QIST, NSF, ...