Small programmable quantum computer with atomic qubits
A programmable quantum computer

Deutsch-Jozsa algorithm

1.12.2014

User interface
- Quantum algorithms: Deutsch–Jozsa, QFT, etc.

Quantum compiler
- Universal gates: Hadamard, CNOT, CP, etc.
- Native gates: XX-gates, R-gates

Quantum control
- Pulse shaping: optimization of XX- and R-gates

Hardware
- Optical addressing: qubit manipulation/detection
- Qubit register: ion trap, Yb ion chain, etc.
Prior examples: IBM Quantum Experience QX

May, 2016:

- Cloud-based quantum computer
- 5 transmonic qubits
- Limited set of two-qubit interaction

Now:

- Systems up to 20 qubits
- Programmability through Python API and SDK

Source: https://quantumexperience.ng.bluemix.net/qx/devices
Trapping ions: the Paul trap

**Earnshaw's theorem**: charged particles cannot be trapped in a stable configuration with static electric fields only → time dependent electric fields (RF)

Dynamical electric field:
- two pairs of electrodes: confinement in $x$ and $y$ directions ($\nu_{x-y} = 3.07 \text{ MHz}$)
- end cap electrodes: confinement in the $z$ direction ($\nu_z = 0.27 \text{ MHz}$)

Ion chain with spacing determined by Coulomb repulsion and axial confinement

Video: [https://youtu.be/XTJznUkAmIY?t=1m](https://youtu.be/XTJznUkAmIY?t=1m)
Ions as qubits

- two states $|g\rangle$ and $|e\rangle$ with long lifetime ($\sim$ sec) for qubit
- One state with short lifetime for measuring
- Weak transition $\Rightarrow$ slow gates
- Usually energy gap between $|g\rangle$ and $|e\rangle$ small $\Rightarrow$ long wavelength
Raman Transition

- Use two highly detuned lasers (big $\Delta$) to not populate $|1\rangle$
- Raman frequency $\alpha$ laser intensity
- Frequency difference of lasers = Frequency difference of states

$|g\rangle$ $\rightarrow$ $|e\rangle$

$|1\rangle$ $\rightarrow$ $\Delta$

Raman transition,
Ions as qubits in $^{172}$Yb$^+$

Atomic Qubit Manipulation

Energie level of $^{172}$Yb$^+$
- $|g\rangle$ and $|e\rangle$ form due to hyperfine splitting
- Purple: Raman transition

Ref: Demonstration of a small programmable quantum computer with atomic qubits
Single qubit gate

\[ R_\Phi(\Theta) = \begin{bmatrix} \cos\left(\frac{\Theta}{2}\right) & -i\sin\left(\frac{\Theta}{2}\right)e^{-i\Phi} \\ -i\sin\left(\frac{\Theta}{2}\right)e^{i\Phi} & \cos\left(\frac{\Theta}{2}\right) \end{bmatrix} \]

- \( R_\Phi(\Theta) \): Rotation on the Bloch sphere
- \( \Theta \) determined by the duration of Raman Transition
- \( \Phi \) determined by phase offset
- \( \pi \) pulse \( \sim \) 23 us
Internal and external degrees of freedom

- In each trapped ion we can isolate a **two-level system**

- The potential close to the trap’s center is harmonic → motional states of ions can be described as **normal modes**

The dressed states of our system → we can **control vibrational modes through sideband transition**
Double qubit gate XX-gate

- We apply a double qubit gate by addressing two Raman beams to the qubits of interest in order to achieve sideband transitions.
- Gate duration is around 235 us.

\[ |\downarrow\downarrow, N\rangle + |\uparrow\uparrow, N\rangle \left/ \sqrt{2} \right. \]
Double qubit gate XX-gate

- Interaction between arbitrary qubits is achieved since the phonons are quantized modes of the center-of-mass (COM) oscillation shared by all ions in the trap.

- COM-mode acts as a quantum bus:

- Intrinsic long-range interactions between any pair of qubits:
  → Fully Connected Spin-Spin Ising Interaction
Double qubit gate XX-gate

• More in general, we can apply a double qubit gate depending by a geometric phase $\chi_{ij}$, controlled by tuning Raman beam intensity:

$$XX(\chi_{ij}) = \begin{bmatrix}
\cos(\chi_{ij}) & 0 & 0 & -i\sin(\chi_{ij}) \\
0 & \cos(\chi_{ij}) & -i\sin(\chi_{ij}) & 0 \\
0 & -i\sin(\chi_{ij}) & \cos(\chi_{ij}) & 0 \\
-i\sin(\chi_{ij}) & 0 & 0 & \cos(\chi_{ij})
\end{bmatrix}$$

• This gate is used in order to create C-NOT gate and Phase gate
Double qubit gate $XX$-gate

\[ a_{ij} = \text{sgn}(\chi_{ij}) \] depends on the Coulomb interaction between qubits $i$ and $j$. 
# Computation Architecture

| Hardware | Optical addressing: qubit manipulation/detection  
Qubit register: ion trap, Yb ion chain, etc. |
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantum control</td>
<td>Pulse shaping: optimization of XX- and R-gates</td>
</tr>
</tbody>
</table>
| Quantum compiler | Universal gates: Hadamard, CNOT, CP, etc. 
Native gates: XX-gates, R-gates |
| User interface | Quantum algorithms: Deutsch–Jozsa, QFT, etc. |

Diagram showing hardware components and connections.
Control

Multi-channel Acousto-Optic Modulator (AOM)

Used in the experiment to control the properties of the light:
- Frequency
- Phase
- Intensity
Control

Multi-channel Acousto-Optic Modulator (AOM)

Used in the experiment to control the properties of the light:

- **Frequency**
  tuned by the sound wave frequency (in the order of 100 Mhz) due to Doppler effect

- **Phase**
  tuned by the sound wave phase by an arbitrary amount

- **Intensity:**
  the higher the intensity of the sound, the higher the modulation

With AOMs the Raman beams are focused down to a beam waist of 1.5 um, having a crosstalk <4%
Detection

Multi-channel photo-multiplier tube (PMT)

Single photon detection, with a resolution of 0.55 um
4 Different Algorithms

- Deutsch – Jozsa
- Bernstein–Vazirani
- Coherent quantum Fourier transform
  - Period finding
  - Phase estimation
Deutsch – Jozsa

- Implemented for 3 Qubits
- Determines whether function is constant or balanced
  - If measurement $= |111\rangle = |7\rangle \rightarrow$ Constant
  - Otherwise $\rightarrow$ Balanced
Deutsch – Jozsa

- Fidelity 95%
- Fidelity = average success rate
- Drops with number of applied gates
Bernstein–Vazirani

- Similar to Deutsch-Jozsa
- Uses $F_c(x) = c \cdot x = c_1 x_1 + c_2 x_2 + \ldots$ for oracle
  - $c, \in \{0, \ldots, 2^n - 1\}$, $c = (c_1, c_2, \ldots, c_n)$ (bitwise notation)
- Determines $c$ in one shot measurement
Bernstein–Vazirani

- Fidelity: 90%
- Drops with number of applied gates
Quantum Fourier transform

- Series of H and CP gates
- Used in various Algorithms: e.g. Shor’s Algorithm
- Tested in
  - Period finding
  - Phase estimation
Phase estimation

- Measures Output State $k \in \{0, \ldots, 2^n - 1\}$, $n = 5$ to find unknown phase $\phi \approx k \frac{2\pi}{N}$
- 80 Gates involved
- Fidelity 62%
Current Fidelity limited by native gate errors
- Raman beam intensity noise
- Individual addressing crosstalk

Scaling in single linear Trap
- “to dozens of qubits”
  - Software calibration for XX and R gates ~ $O(n^2)$
  - XX-gate Slow down ~ $O(n^{1.7})$
    - due to weakening of axial confinement

Further scaling with multi-zone ion traps