Quantum Logic Gates with Trapped Ions

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Summary

1. Trapping Ions
2. Cooling Ions
3. Manipulating Ions States
4. The Controlled-NOT Gate

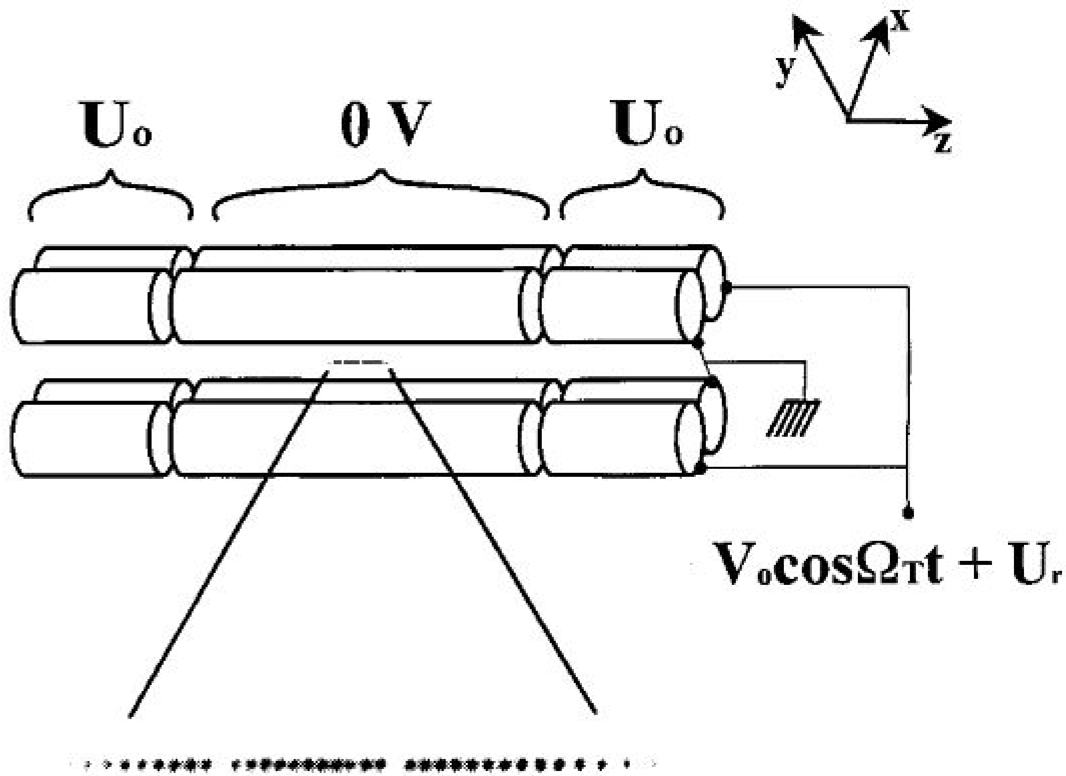
1. Trapping Ions

1.1. Basic Ideas

- **Ions are charged atoms: electromagnetic fields can be used to confine them.**
- **Earnshaw’ Theorem: No stable confinement in three dimensions with static fields.**
- **Paul Trap: radio frequency quadrupole field**

1. Trapping Ions

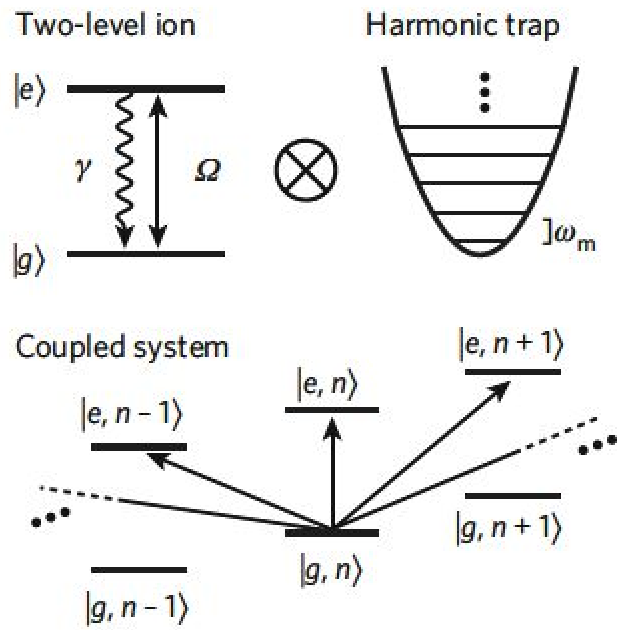
1.2. The Linear Paul Trap



Schematic Representation of a Linear Paul Trap

1. Trapping Ions

1.3. Energy Levels of a Trapped Ion



Energy levels of a two-levels trapped ion

2. Cooling Ions

2.1. Basic Ideas

Reducing the momentum of the ion by creating an asymmetry in the absorption-emission cycle

Radiation Pressure

Doppler Effect

2. Cooling Ions

2.2. Doppler cooling

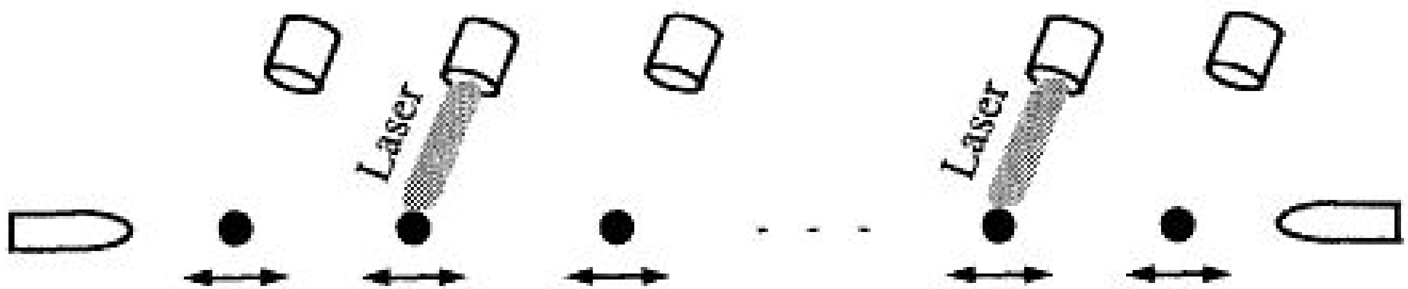
Weak Binding Limit: the ion undergoes a large number of cooling cycles during one oscillation period in the trap

2.2. Resolved Sideband Cooling

Strong Binding Limit: the ion goes through a large number of oscillation periods during one cooling cycle

3. Manipulating Ions States

3.1. A simple scheme



Ions chain in a linear Paul trap
Individual ions can be addressed by focused lasers
Ions are coupled through collective motional modes

3. Manipulating Ions States

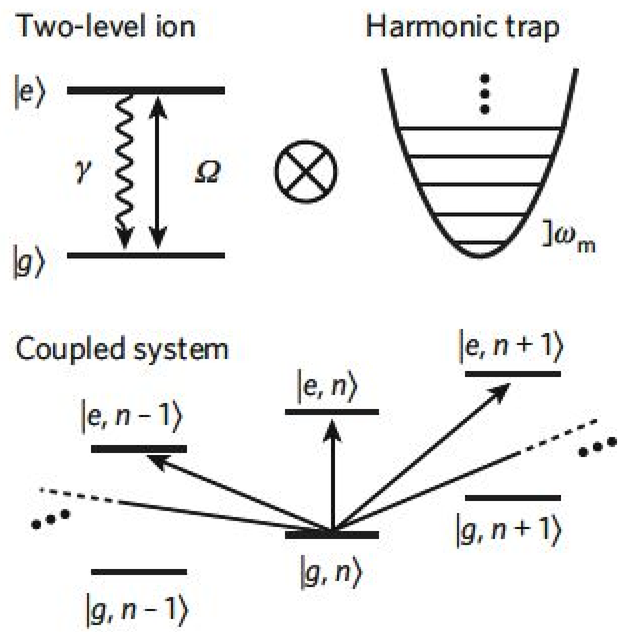
3.2. Interaction with Electromagnetic Fields

$$\Psi(t) = \begin{bmatrix} \cos\Omega_{n',n}t & -i\,e^{i[\phi+\frac{\pi}{2}|n'-n|]}\sin\Omega_{n',n}t \\ -i\,e^{-i[\phi+\frac{\pi}{2}|n'-n|]}\sin\Omega_{n',n}t & \cos\Omega_{n',n}t \end{bmatrix} \Psi(0)$$

Evolution of the ion state under the influence of a propagating electromagnetic field

3. Manipulating Ions States

3.3. Playing with the Laser Frequency



Laser on carrier transition: manipulation of the internal state

Laser on a sideband: entanglement of internal states and motional states

3. Manipulating Ions States

3.4. Playing with the Pulse Duration

- **π pulse: population inversion**
- **2 π pulse: sign change**
- **$\pi/2$ pulse: superposition of both states**

4. The C-NOT Gate

4.1. Truth Table

$$\text{Input state} \longrightarrow \text{Output state}$$

$$|0\rangle|\downarrow\rangle \longrightarrow |0\rangle|\downarrow\rangle$$

$$|0\rangle|\uparrow\rangle \longrightarrow |0\rangle|\uparrow\rangle$$

$$|1\rangle|\downarrow\rangle \longrightarrow |1\rangle|\uparrow\rangle$$

$$|1\rangle|\uparrow\rangle \longrightarrow |1\rangle|\downarrow\rangle .$$

State of the Target Bit is flipped when the Control Bit is 1

4. The C-NOT Gate

4.2. Realization with a single Ion

Control Bit: Quantized State of Motion

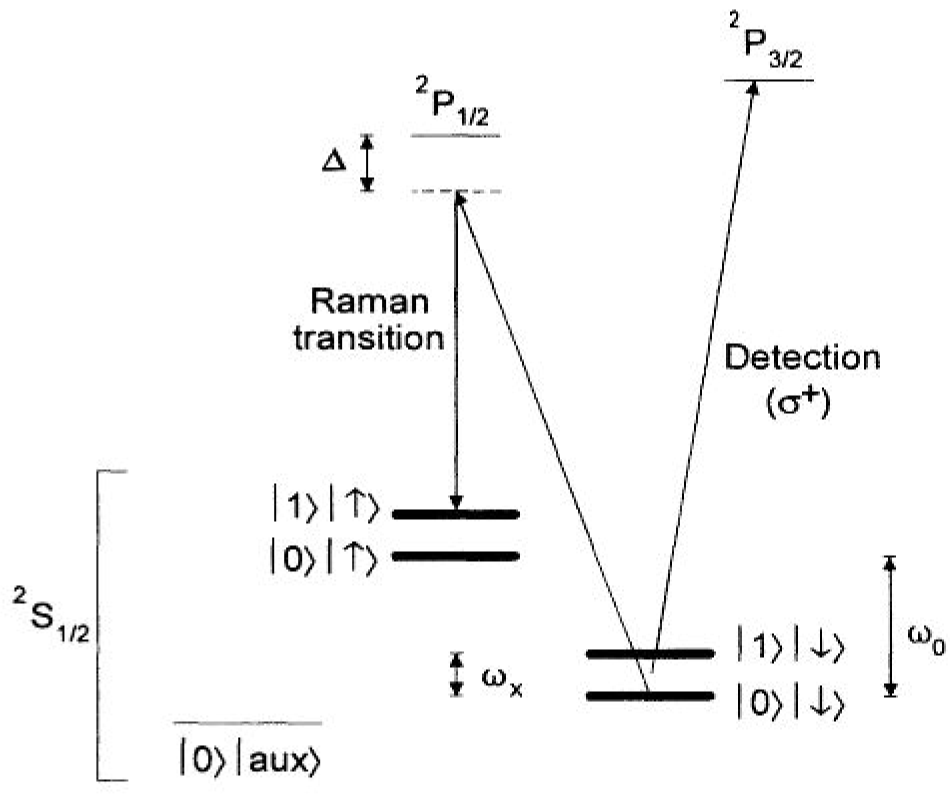
Target Bit: Internal State of the Ion

C-NOT Gate can be implemented by applying a series of three pulses to the ion:

1. **$\pi/2$ pulse on the carrier transition**
2. **2π pulse on the first blue sideband**
3. **$\pi/2$ pulse on the carrier transition (with a phase-shift of π with respect to the first one)**

4. The C-NOT Gate

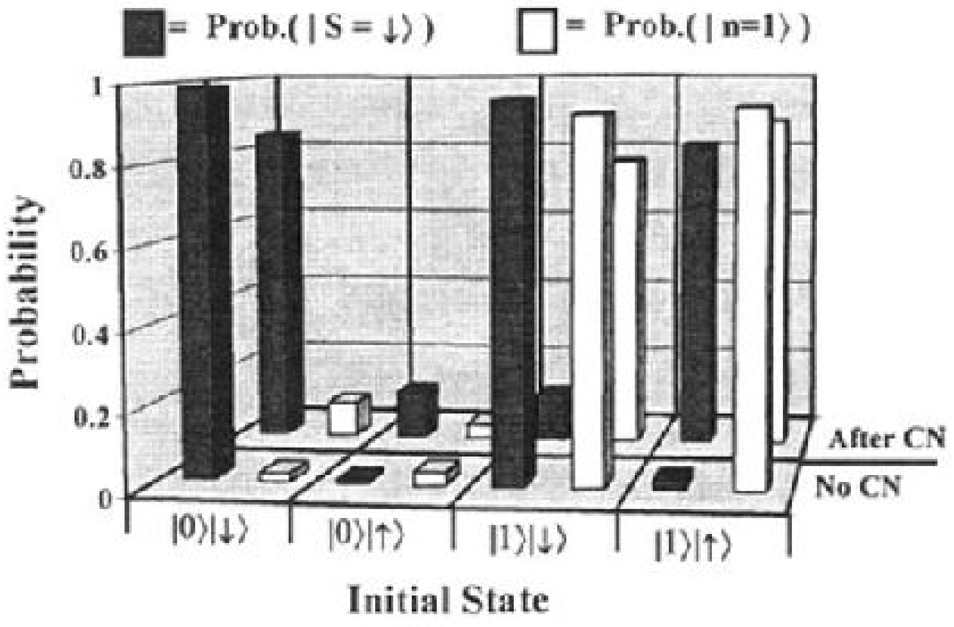
4.3. Realization with a Single Beryllium Ion



Level scheme of Beryllium Ion

4. The C-NOT Gate

4.3. Realization with a Single Beryllium Ion



C-NOT truth table measurements

4. The C-NOT Gate

4.4. Realization with Two Ions

Control Bit: Internal State of First Ion

Target Bit: Internal State of Second Ion

C-NOT Gate can be implemented by applying a series of three pulses to the ion:

1. Control Ion: π pulse on the first red sideband
2. Target Ion: C-NOT gate
3. Control Ion: π pulse on the first red sideband (with a phase shift of π with respect to 1.)