

# Trapped Ion Quantum Computing

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# Basics of Quantum Computing

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# Qubits

- Analog to the classical bit (Qubit = Quantum bit)
- Any two-state quantum system can theoretically be a qubit
- We use our familiar Dirac notation to represent states

$$|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \text{ and } |1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

- Qubits can have a superposition unlike a classical bit

$$\begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \alpha |0\rangle + \beta |1\rangle$$

# Electron Spin

- Electron spin is a familiar two-state quantum system
- Recall our spin operators for the different dimensions

$$S_x = \frac{\hbar}{2} \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \quad S_y = \frac{\hbar}{2} \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} \quad S_z = \frac{\hbar}{2} \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

- $\begin{bmatrix} 1 \\ 0 \end{bmatrix} = |0\rangle$  and  $\begin{bmatrix} 0 \\ 1 \end{bmatrix} = |1\rangle$  are the z-basis eigenvectors
- Observe how these basis vectors can map to the Pauli spin matrices

$$\begin{aligned} |0\rangle \langle 0| + |1\rangle \langle 1| &= I & |0\rangle \langle 1| + |1\rangle \langle 0| &= \sigma_x \\ i(|0\rangle \langle 1| - |1\rangle \langle 0|) &= \sigma_y & |1\rangle \langle 1| - |0\rangle \langle 0| &= \sigma_z \end{aligned}$$

# Unitary Operators

- The evolution of a quantum system is described by unitary operators

$$|\psi_t\rangle = U(t, t_0) |\psi_0\rangle$$

- Unitary Operators are *mathematically reversible*:

$$UU^\dagger = I$$

- You can apply unitary operators to a qubit to alter its state in a desirable manner

# Quantum Gates

- In quantum computing, unitary operators are usually called **quantum gates**
- Many of the basic quantum gates are look very familiar!

$$X = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \quad Y = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} \quad Z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

- There are also less familiar gates such as the *Hadamard* Gate:

$$H = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

- The X gate is also called the NOT gate:

$$NOT |0\rangle = |1\rangle \text{ and } NOT |1\rangle = |0\rangle$$

$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} \beta \\ \alpha \end{bmatrix}$$

- The Hadamard gate creates a superposition:

$$\frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ 1 \end{bmatrix} = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

# Quantum Circuits

- A series of quantum gates constitutes a **quantum circuit**
- It is standard to represent these as if they were on a wire



$$ZYH |0\rangle = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} -i \\ -i \end{bmatrix}$$



# Basics of Trapped Ion Quantum Systems

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# Why Use Trapped Ions?

- Qubits need to be isolated from the rest of the universe
- An ion is much easier to manipulate than a neutral atom
- They have exceptionally long coherence times
- Quantum gates have been implemented with exceptional fidelity
- Quantum states are easy to prepare and measure
- The physics behind them is well understood and relatively simple

## Encoding a Trapped Ion with a Qubit

Take any two long-lived states of different energies  $|g\rangle$  and  $|e\rangle$

Just like spin, these states can map to the Pauli spin matrices:

$$\begin{aligned} |g\rangle\langle g| + |e\rangle\langle e| &= I & |g\rangle\langle e| + |e\rangle\langle g| &= \sigma_x \\ i(|g\rangle\langle e| - |e\rangle\langle g|) &= \sigma_y & |e\rangle\langle e| - |g\rangle\langle g| &= \sigma_z \end{aligned}$$

We can think of  $|g\rangle$  as  $|0\rangle$  and  $|e\rangle$  as  $|1\rangle$

The two-level Hamiltonian is represented by

$$\hat{H} = \hbar(\omega_g |g\rangle\langle g| + \omega_e |e\rangle\langle e|) \rightarrow \hat{H} = \hbar\frac{\omega_0}{2}\sigma_z$$

# Measuring a Qubit

- Detection of states involves photon scattering
- States are carefully chosen so one "bright" state scatters incoming photons while the other has no effect
- The trajectories of the photons are detected, making it easy to tell which qubits scattered the photons

# What Ions Make Good Qubits?

- There are a few features that are desirable in an ion:
  - Hydrogen-like atomic structure
  - Singly ionized species
  - Metastable states in the visible spectrum
- This makes heavier alkali earth metals a common choice

# Rabi Frequencies

The Rabi frequency comes up when a two-state system is placed in an electric field

This frequency is the rate at which the the system 'flops' between states

Rabi frequencies are a way to measure the strength of the coupling of the states and the field applied defined by

$$\Omega = -\frac{\langle e | \vec{\mu} \cdot \vec{\epsilon} E_0 | g \rangle}{\hbar}$$

# Classical Ion Trapping

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# Classical Ion Trapping

- Static electric fields cannot trap an ion
  - Gauss's law  $\nabla \cdot E = 0 \rightarrow$  electric potential has no local minima
  - This is overcome by varying the electric field with time
- These traps typically have potentials oscillating in the radio frequency range
- Construct a trap with a time-varying and time-independent part:

$$V(x, y, z, t) = U \frac{1}{2} (\alpha x^2 + \beta y^2 + \gamma z^2) + \tilde{U} \cos(\omega_r t) \frac{1}{2} (\alpha' x^2 + \beta' y^2 + \gamma' z^2)$$



# Classical Ion Trapping

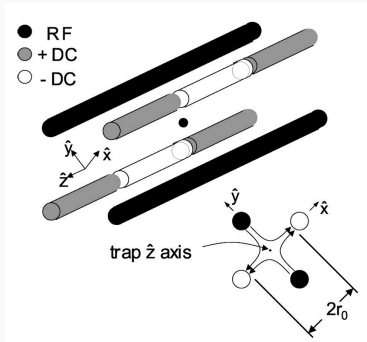
$$V(x, y, z, t) = U \frac{1}{2} (\alpha x^2 + \beta y^2 + \gamma z^2) + \tilde{U} \cos(\omega_{rf} t) \frac{1}{2} (\alpha' x^2 + \beta' y^2 + \gamma' z^2)$$

Laplace's Equation ( $\nabla^2 V = 0$ ) says:

$$\begin{aligned}\alpha + \beta + \gamma &= 0 \\ \alpha' + \beta' + \gamma' &= 0\end{aligned}$$

Which is underconstrained – there are many ways to place electrodes

# Linear Paul Trap



A Linear Paul Trap from "Quantum dynamics of single trapped ions" 2003

$$\begin{aligned} -(\alpha + \beta) &= \gamma \\ \alpha' &= -\beta' \end{aligned}$$

# Classical Ion Trapping

- The problem can be one-dimensionalized:

$$\ddot{x} = -\frac{Ze}{m} \frac{\partial V}{\partial x} = -\frac{Ze}{m} [U\alpha + \tilde{U} \cos(\omega_{rf}t)\alpha']x$$

- And transformed into a Mathieu differential equation:

$$\frac{d^2x}{d\xi^2} + [a_x - 2q_x \cos(2\xi)]x = 0$$

with

$$\xi = \frac{\omega_{rf}t}{2}, \quad a_x = \frac{4ZeU\alpha}{m\omega_{rf}^2}, \quad q_x = \frac{2Ze\tilde{U}\alpha'}{m\omega_{rf}^2}$$

# Classical Ion Trapping

Mathieu differential equations have solution

$$x(\xi) = A e^{i\beta_x \xi} \sum_{n=-\infty}^{\infty} C_{2n} e^{i2n\xi} + B^{-i\beta_x \xi} \sum_{n=-\infty}^{\infty} C_{2n} e^{-i2n\xi}$$

where  $\beta_x$  and  $C_{2n}$  are functions of  $a_x$  and  $q_x$ .

Assuming  $|a_x|, q_x^2 \ll 1$ ,  $\beta \approx \sqrt{a_x + \frac{q_x^2}{2}}$ , and (to first order):

$$x(t) \propto \cos\left(\beta_x \frac{\omega_{rf}}{2} t\right) \left[1 - \frac{q_x}{2} \cos(\omega_{rf} t)\right]$$

# Quantum Ion Trapping

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# Quantum Ion Trapping

Begin with our same potential, but rewrite it:

$$V(t) = \frac{m}{2}W(t)\hat{x}^2 \quad \text{with} \quad W(t) = \frac{\omega_{rf}^2}{4}[a_x - 2q_x \cos(\omega_{rf}t)]$$

This looks familiar! We already know the solutions to

$$V(x) = \frac{1}{2}m\omega x^2$$

Maybe there are some raising and lowering operators...

# Quantum Ion Trapping

Our Hamiltonian of motion can be written,

$$\hat{H}^{(m)} = \frac{\hat{p}^2}{2m} + \frac{m}{2}W(t)\hat{x}^2$$

First, we can write the operators in the Heisenberg picture:

$$\begin{aligned}\dot{\hat{x}} &= \frac{1}{i\hbar}[\hat{x}, \hat{H}^{(m)}] = \frac{\hat{p}}{m} \\ \dot{\hat{p}} &= \frac{1}{i\hbar}[\hat{p}, \hat{H}^{(m)}] = -mW(t)\hat{x}\end{aligned}$$

which combine into a Mattheiu equation!

$$\begin{aligned}\ddot{\hat{x}} + W(t)\hat{x} &= 0 \\ \ddot{\hat{x}} + \frac{\omega_{rf}^2}{4}[a_x - 2q_x \cos(\omega_{rf}t)]\hat{x} &= 0\end{aligned}$$

# Quantum Ion Trapping

Consider some other  $u(t)$  that satisfies the same equation:

$$\ddot{u}(t) + W(t)\hat{u}(t) = 0$$

with boundary conditions  $u(0) = 1$ ,  $\dot{u}(0) = iv$

From before, with  $A = 0$  and  $B = 1$

$$u(t) = e^{i\beta_x\omega_{rf}/2} \sum_{n=-\infty}^{\infty} C_{2n} e^{in\omega_{rf}t} \equiv e^{i\beta_x\omega_{rf}/2} \Phi(t)$$

Applying the boundary conditions,

$$u(0) = \sum_{n=-\infty}^{\infty} C_{2n} = 1, \quad v = \omega_{rf} \sum_{n=-\infty}^{\infty} C_{2n}(\beta_x/2 + n)$$



# Quantum Ion Trapping

Since  $u(t)$  and  $\hat{x}$  satisfy the same differential equation, so

$$\hat{C}(t) = \sqrt{\frac{m}{2\hbar v}} i [u(t)\dot{\hat{x}} - \dot{u}(t)\hat{x}]$$

is proportional to their Wronskian identity, and is constant in time

$$\hat{C}(t) = \hat{C}(0) = \frac{1}{\sqrt{2m\hbar v}} (mv\hat{x}(0) + i\hat{p}(0)) = \hat{a}$$

We have recovered exactly the lowering operator!

# Quantum Ion Trapping

Using this relation, we can write our operators in terms of  $\hat{a}$  and  $\hat{a}^\dagger$ :

$$\hat{x}(t) = \sqrt{\frac{\hbar}{2m\nu}} [\hat{a}u^*(t) + \hat{a}^\dagger u(t)]$$

$$\hat{p}(t) = \sqrt{\frac{\hbar m}{2\nu}} [\hat{a}\dot{u}^*(t) + \hat{a}^\dagger \dot{u}(t)]$$

And just like we're used to, we have a state  $|n=0\rangle_v$  such that

$$\hat{a} |n=0\rangle_v = 0$$

In the Schrödinger picture ( $\hat{U}(t) = e^{-(i/\hbar)\hat{H}^{(m)}}$ ):

$$\hat{C}_S(t)\hat{U}(t) |n=0\rangle_v = \hat{C}_S(t) |n=0, t\rangle = 0$$

# Quantum Ion Trapping

These states form a complete orthonormal basis via the creation operator:

$$|n, t\rangle = \frac{[\hat{C}_S^\dagger(t)]^n}{\sqrt{n!}} |n=0, t\rangle$$

Excluding a phase factor, the ground state is approximately

$$\begin{aligned} \chi_0(t) = & \left(\frac{mv}{\pi\hbar}\right)^{1/4} \sqrt{\frac{1 + q_x/2}{1 + (q_x/2) \cos(\omega_{rf}t)}} \\ & \times \exp\left(\left[i \frac{m\omega_{rf} \sin(\omega_{rf}t)}{2\hbar[2/q_x + \cos(\omega_{rf}t)]} - \frac{mv}{2\hbar}\right] x^2\right) \end{aligned}$$

If  $\omega_{rf} = 0$ , the solution is exactly the harmonic oscillator.

# Quantum Gate Implementation

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# Rotation Gates

We use lasers to change states

The total Hamiltonian can be written as a sum of the ion's internal electron state, its motional state, and the interaction with the laser:

$$\hat{H} = \hat{H}_E + \hat{H}_M + \hat{H}_L$$

The laser Hamiltonian is defined by  $\Omega$ ,  $\omega$ ,  $k$ , and  $\phi$

$$\hat{H}_L = \frac{\hbar\Omega}{2}(\hat{\sigma}^+ + \hat{\sigma}^-)[e^{i(k\hat{x}-\omega t+\phi)} + e^{-i(k\hat{x}-\omega t+\phi)}]$$

But this problem is much easier in the *interaction picture*

Let  $\hat{H}_0 = \hat{H}_E + \hat{H}_M$  and  $\hat{U}_0 = e^{-(i/\hbar)\hat{H}_0 t}$ , so

$$\hat{H}_{int} = \hat{U}_0^\dagger \hat{H}_L \hat{U}_0.$$

After plugging in and much simplification and approximation

$$\hat{H}_{int}(t) = \frac{\hbar\Omega}{2} [e^{i\eta(\hat{a}^\dagger e^{i\omega t} + \hat{a} e^{-i\omega t})} \hat{\sigma}^+ e^{-i((\omega - \omega_0)t - \phi)} + h.c.]$$

We get resonance when  $\omega - \omega_0$  is small and the  $\phi$  term dominates

# Rotation Gates

When the phase term dominates:

$$\hat{H}_{int} = \frac{\hbar\Omega}{2}(\hat{\sigma}^+ e^{i\phi} + \hat{\sigma}^- e^{-i\phi}) \equiv \frac{\hbar\Omega}{2}\hat{\sigma}_\phi$$

And this Hamiltonian describes rotation gates!

Let's put this back into the Schrödinger equation:

$$\frac{d}{dt} |\psi(t)\rangle = -\frac{i}{\hbar} \hat{H} |\psi(t)\rangle \rightarrow |\psi(t)\rangle = e^{-\frac{i\Omega}{2}t\hat{\sigma}_\phi} |\psi(0)\rangle \equiv \hat{U}(t) |\psi(0)\rangle$$

So we have a unitary operator evolving the system...

# Rotation Gates

Letting  $\Omega t \equiv \theta$ :

$$\begin{aligned}\hat{U}(t) &= \sum_{k=0}^{\infty} \frac{1}{k!} \left(-i \frac{\theta}{2} \hat{\sigma}_{\phi}\right)^k = \\ &I \sum_{k=0}^{\infty} \frac{(-1)^k}{(2k)!} \left(\frac{\theta}{2}\right)^{2k} - i \hat{\sigma}_{\phi} \sum_{k=0}^{\infty} \frac{(-1)^k}{(2k+1)!} \left(\frac{\theta}{2}\right)^{2k+1} = \\ &I \cos\left(\frac{\theta}{2}\right) - i \hat{\sigma}_{\phi} \sin\left(\frac{\theta}{2}\right) = \begin{pmatrix} \cos \frac{\theta}{2} & -i \sin \frac{\theta}{2} e^{-i\phi} \\ -i \sin \frac{\theta}{2} e^{i\phi} & \cos \frac{\theta}{2} \end{pmatrix}\end{aligned}$$

We recover the  $X$ ,  $Y$ , and  $Z$  gates with the right choices of  $\theta$  and  $\phi$ !!



## Conclusion





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# Conclusion

- Trapped ion systems have incredible physics and we barely scratched the surface:
  - There are many more gates that have been implemented, including the Hadamard gate and other multi-qubit gates
  - This presentation only talked about single ion systems, but many ions can be trapped at once
  - There are multiple different kinds of states used as the two state system
- Nonetheless, a large portion of trapped ion dynamics can be described with what we have learned in this class!

# References

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Questions?