Trapped-ion Quantum Computation introduction

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Outline

1. **Background**
   - Quantum numbers
   - Cooling techniques
   - Ion trapping methods
2. **Qubit types**
3. **Qubit control**
   - signal qubit gates
   - multi qubit gates
   - measurement
4. **Scaling**

Quantum numbers

Principal Quantum Number $n = 1, 2, 3, \ldots$

Azimuthal Quantum Number $\ell = 0, \ldots, (n-1)$

Magnetic Quantum Number $m_\ell = -l, \ldots, l$

Electron Spin Quantum Number $m_s = -\frac{1}{2}, +\frac{1}{2}$

Quantum numbers

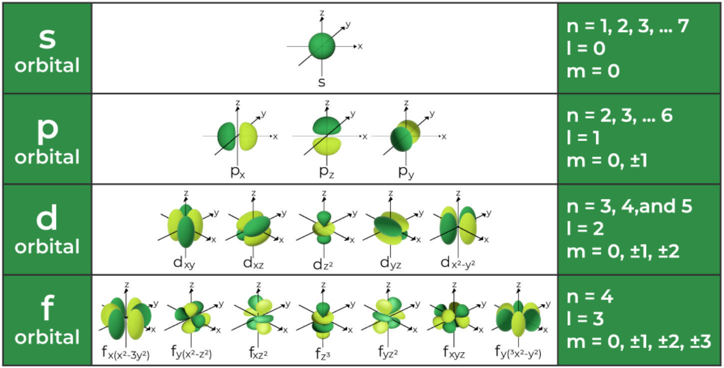

Figure: copy from[1]

[1] https://www.geeksforgeeks.org/quantum-numbers/

important principle

Pauli exclusion principle

Aufbau principle

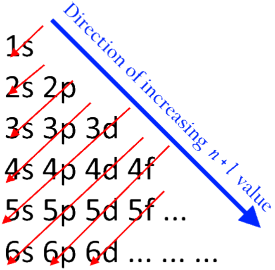

Figure: copy from[2]

[2] **https://en.wikipedia.org/wiki/Aufbau˙principle.**

Examples on Quantum numbers

For Rubidium has the atomic number, Z $= 37$.
Electronic Configuration of Rubidium,$1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 5s^1$

Principal Quantum Number $n = 5$

Azimuthal Quantum Number $l = 0$

Magnetic Quantum Number $m_l = 0$

Spin Quantum Number $m_s = +1/2$

splitting methods

The total angular momentum quantum number: $j = |\ell \pm s|$

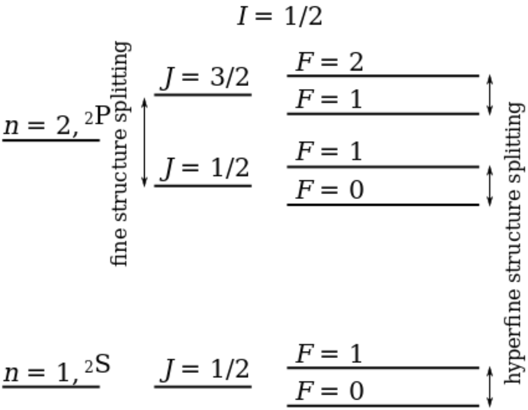

Figure: copy from[3]

[3] **https://en.wikipedia.org/wiki/Hyperfine˙structure.**

doppler cooling

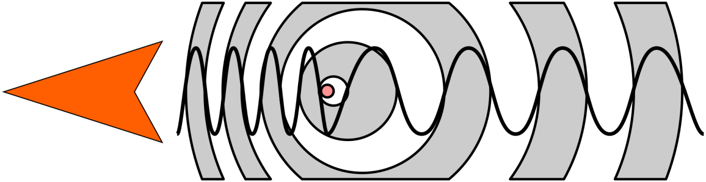

Figure: copy from[4]

[4] **https://en.wikipedia.org/wiki/Doppler˙cooling**.

Resolved sideband cooling

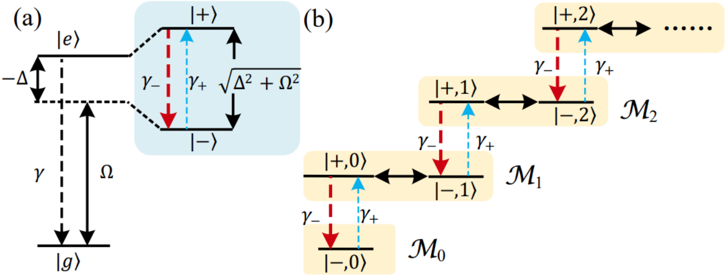

Figure: copy from[5]

[5] https://arxiv.org/pdf/2211.08896.pdf.

paul traps

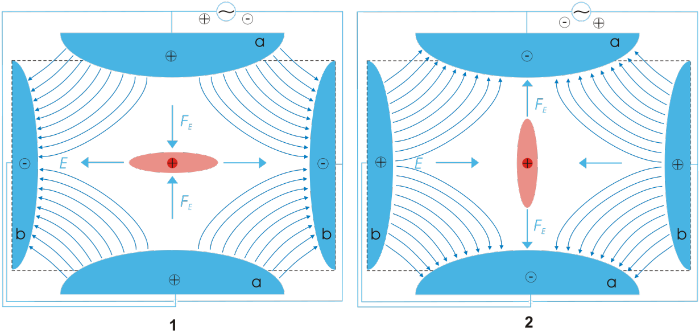

Figure: copy from[6]

[6] https://en.wikipedia.org/wiki/Quadrupole_ion_trap.

penning traps

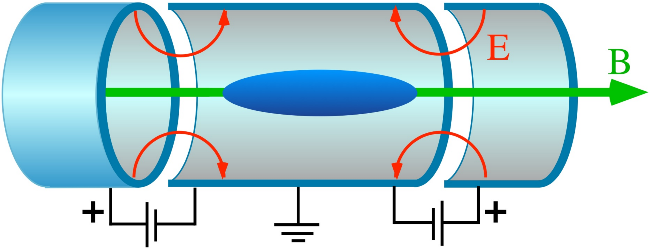

Figure: copy from[7]

[7] https://en.wikipedia.org/wiki/Penning_trap.

Outline

Qubit Type Comparison

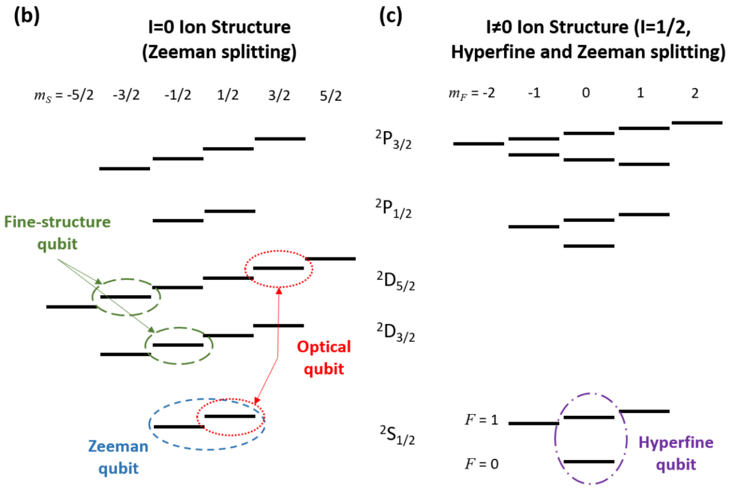

Figure: copy from[8]

[8] https://arxiv.org/abs/1904.04178.

key factors

Abbe diffraction limit $d = \frac{\lambda}{2n \sin \theta} = \frac{\lambda}{2NA}$

Spontaneous emission rate

Magnetic field fluctuations

Laser technical noise

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   - multi qubit gates
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4. Scaling

TABLE I. Selected state-of-the-art gate demonstrations.

Gate Type	Gate Method	Fidelity	Gate Time (μs)	Ion Species	Ref.
Single-Qubit					
	Optical	0.99995	5	$^{40}Ca^{+}$	[28]
	Raman	0.99993	7.5	$^{43}Ca^{+}$	[27]
	Raman	0.99996	2	$^{9}Be^{+}$	[37]
	Raman	0.99	0.00005	$^{171}Yb^{+}$	[163]
	Raman	0.999	8	$^{88}Sr^{+}$	[113]
	Microwave	0.999999	12	$^{43}Ca^{+}$	[22]
	Microwave		0.0186	$^{25}Mg^{+}$	[164]

Figure: copy from[9]

[9] **https://arxiv.org/abs/1904.04178**.

Two Qubit Gates

Cirac-Zoller

Mølmer-Sørensen

Cirac-Zoller

$$
\begin{aligned}
\text{initialize} &\rightarrow (a|g\rangle + b|e\rangle)(c|g\rangle + d|e\rangle)|0\rangle && (1)\\
R_{eg2}^{RSB}(\pi) &\rightarrow (a|g\rangle + b|e\rangle)|g\rangle(c|0\rangle + d|1\rangle) && (2)\\
R_{aux1}^{RSB}(2\pi) &\rightarrow ac|gg0\rangle + ad|gg1\rangle + bc|eg0\rangle - bd\ | && (3)\\
R_{eg2}^{RSB}(\pi) &\rightarrow [ac|gg\rangle + ad|ge\rangle + bc|eg\rangle - bd|ee\rangle]\,|0\rangle && (4)
\end{aligned}
$$

Mølmer-Sørensen

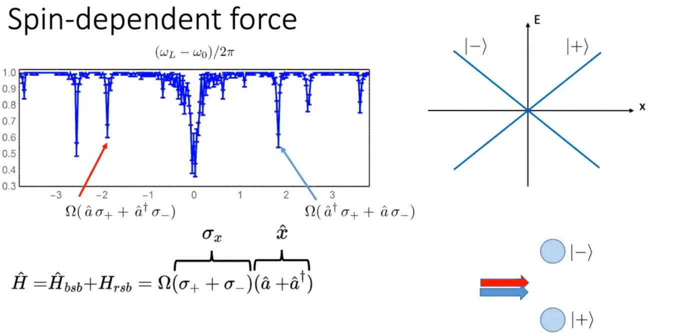

Figure: copy from[10]

[10] **https://www.youtube.com/watch?v=uNTNsfxoKYQ&t=2026s.**

two qubit gates

Fidelity	gate time	Ref
99.9%	$30\mu s$	`https://arxiv.org/abs/1604.00032`
99.8%	$1.6\mu s$	`https://arxiv.org/abs/1709.06952`

average Fidelity $> 98\%$ for any two qubits out of 13 qubits, form IonQ news

challenges for gates

Crosstalk

Laser frequency/amplitude stability

Motional heating (two qubit gates)

...

Outline

challenges for Scaling

$\frac{1}{d^{\alpha}}$: ion-ion coupling strength

errors and Fidelity

gate time (1024-bit $\sim$10 days and 2048-bit number $\sim$100 days)