

Trapped-ion Quantum Computation introduction

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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 $n = 1, 2, 3, \dots$

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

Magnetic Quantum Number $m_\ell = -\ell, \dots, \ell$

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

Quantum numbers


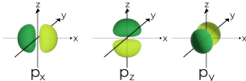
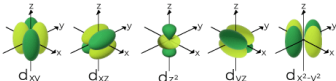
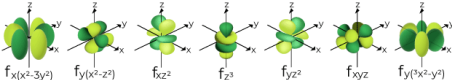
s orbital		$n = 1, 2, 3, \dots 7$ $l = 0$ $m = 0$
p orbital		$n = 2, 3, \dots 6$ $l = 1$ $m = 0, \pm 1$
d orbital		$n = 3, 4, \text{and } 5$ $l = 2$ $m = 0, \pm 1, \pm 2$
f orbital		$n = 4$ $l = 3$ $m = 0, \pm 1, \pm 2, \pm 3$

Figure: copy from¹

¹<https://www.geeksforgeeks.org/quantum-numbers/>

important principle

Pauli exclusion principle

Aufbau principle

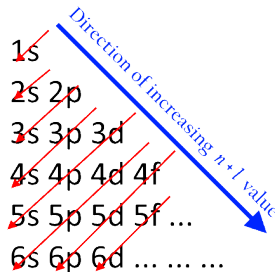


Figure: copy from²

²https://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: $j = |\ell \pm s|$

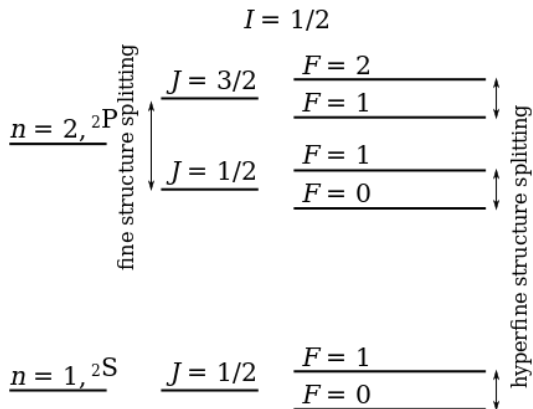


Figure: copy from³

³https://en.wikipedia.org/wiki/Hyperfine_structure.

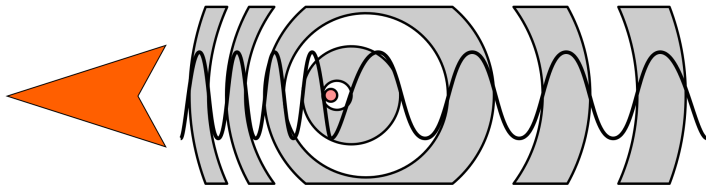


Figure: copy from⁴

⁴https://en.wikipedia.org/wiki/Doppler_cooling.

Resolved sideband cooling

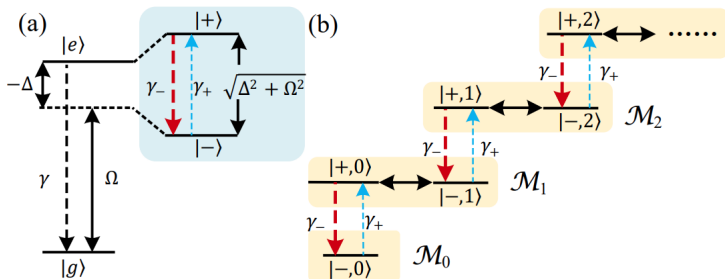


Figure: copy from⁵

⁵<https://arxiv.org/pdf/2211.08896.pdf>.

paul traps

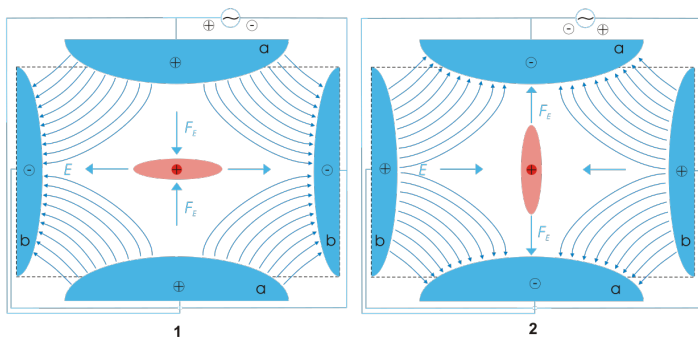


Figure: copy from⁶

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

penning traps

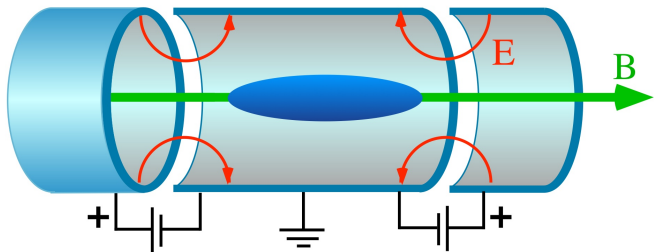


Figure: copy from⁷

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

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Qubit Type Comparison

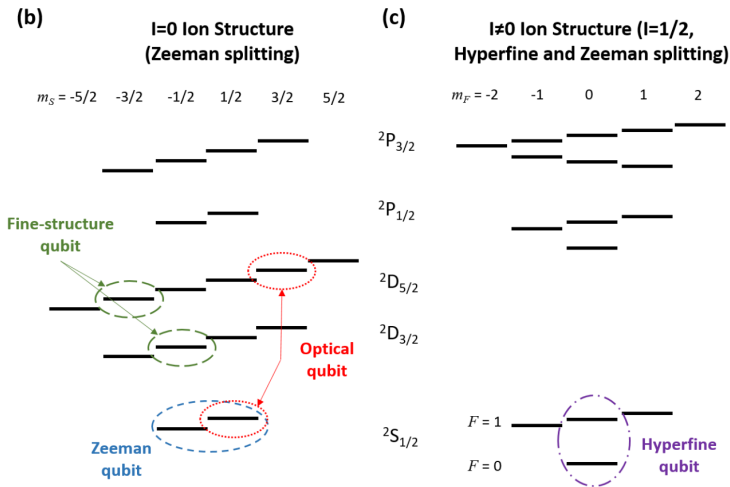


Figure: copy from⁸

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

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

Figure: copy from⁹

⁹<https://arxiv.org/abs/1904.04178>.

Two Qubit Gates

Cirac-Zoller

Mølmer-Sørensen

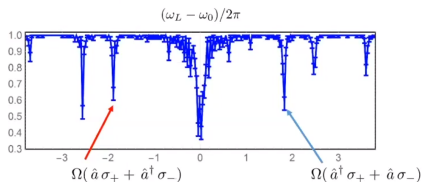
$$\text{initialize} \rightarrow (a|g\rangle + b|e\rangle)(c|g\rangle + d|e\rangle)|0\rangle \quad (1)$$

$$R_{eg2}^{RSB}(\pi) \rightarrow (a|g\rangle + b|e\rangle)|g\rangle(c|0\rangle + d|1\rangle) \quad (2)$$

$$R_{aux1}^{RSB}(2\pi) \rightarrow ac|gg0\rangle + ad|gg1\rangle + bc|eg0\rangle - bd| \quad (3)$$

$$R_{eg2}^{RSB}(\pi) \rightarrow [ac|gg\rangle + ad|ge\rangle + bc|eg\rangle - bd|ee\rangle] |0\rangle \quad (4)$$

Spin-dependent force



$$\hat{H} = \hat{H}_{bsb} + \hat{H}_{rsb} = \overbrace{\Omega(\sigma_+ + \sigma_-)}^{\sigma_x} \overbrace{(\hat{a} + \hat{a}^\dagger)}^{\hat{x}}$$

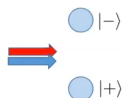
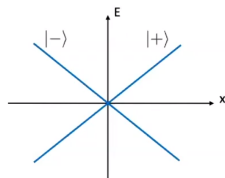


Figure: copy from¹⁰

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, from IonQ news

challenges for gates

Crosstalk

Laser frequency/amplitude stability

Motional heating (two qubit gates)

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challenges for Scaling

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

errors and Fidelity

gate time (1024-bit ~ 10 days and 2048-bit number ~ 100 days)