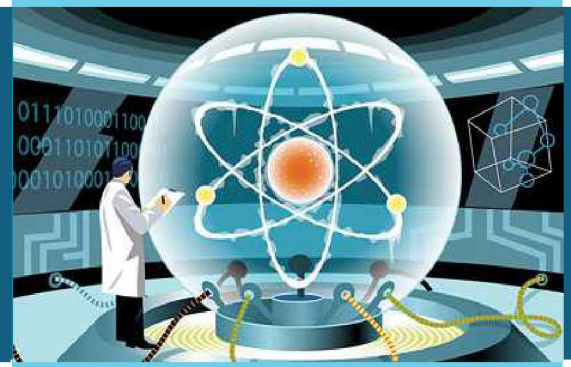
SAND2020-6881PE

Recipe for Building a Quantum Computer, One Atom at a Time



PRESENTED BY

Daniel Lobser

Org. 5225

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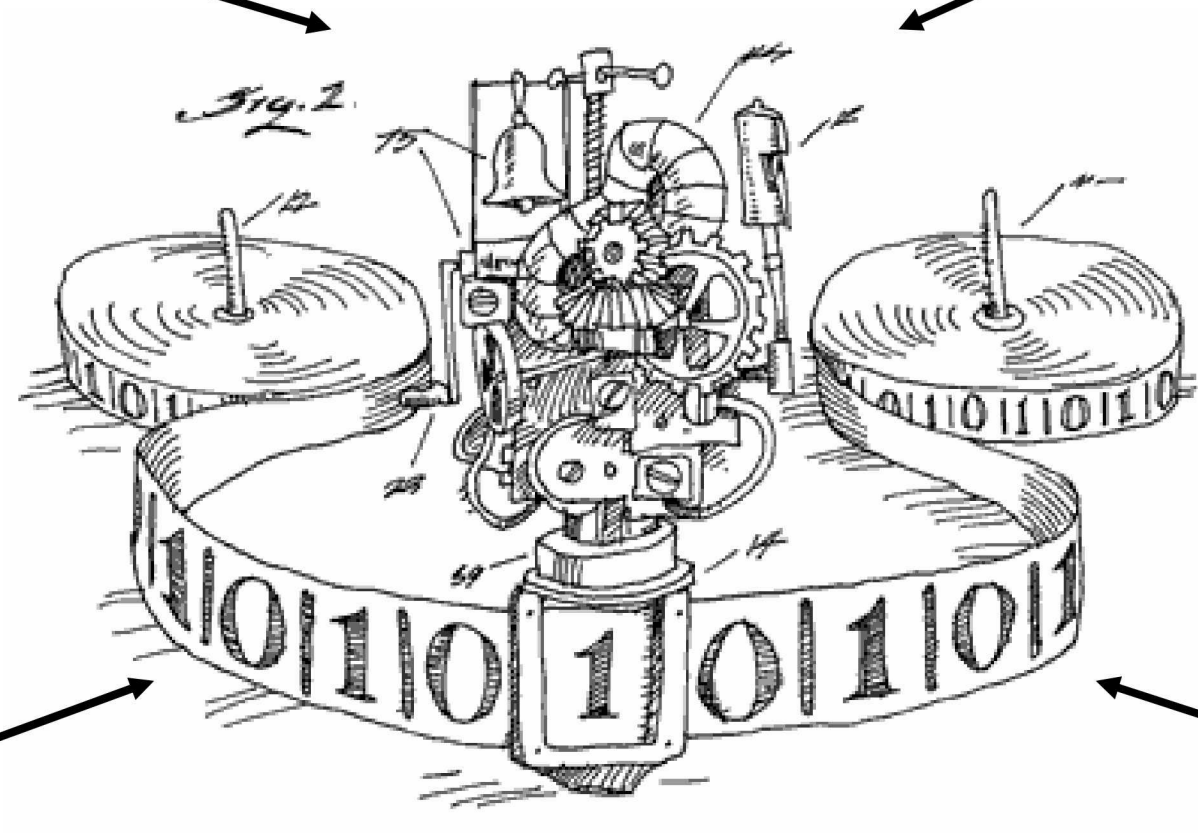
Gates

Quantum Gates

- Superposition
- Entanglement



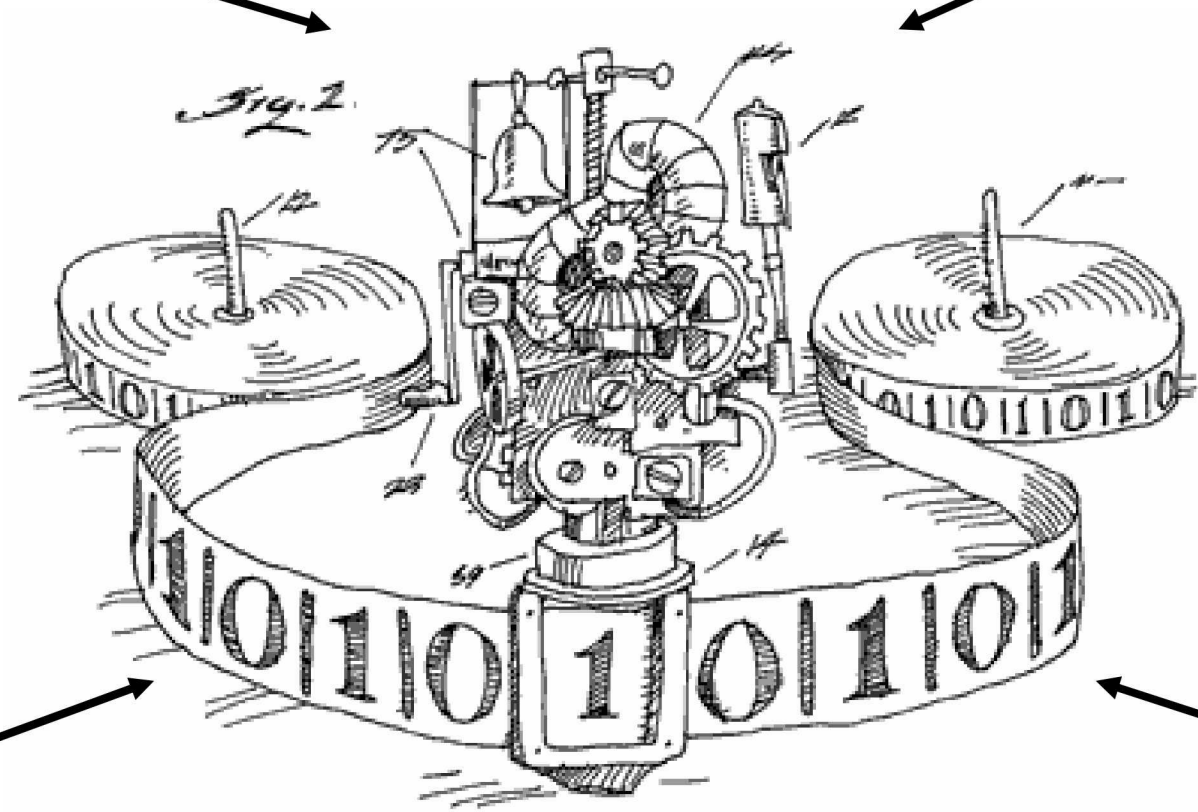
Bits

Qubits

Gates

Quantum Gates

- Superposition
- Entanglement

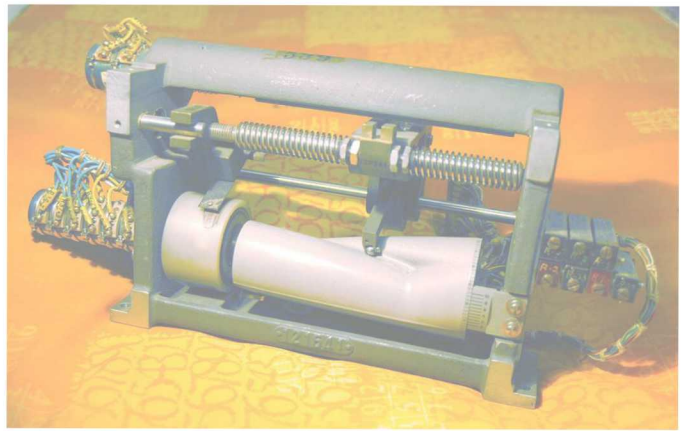


Bits

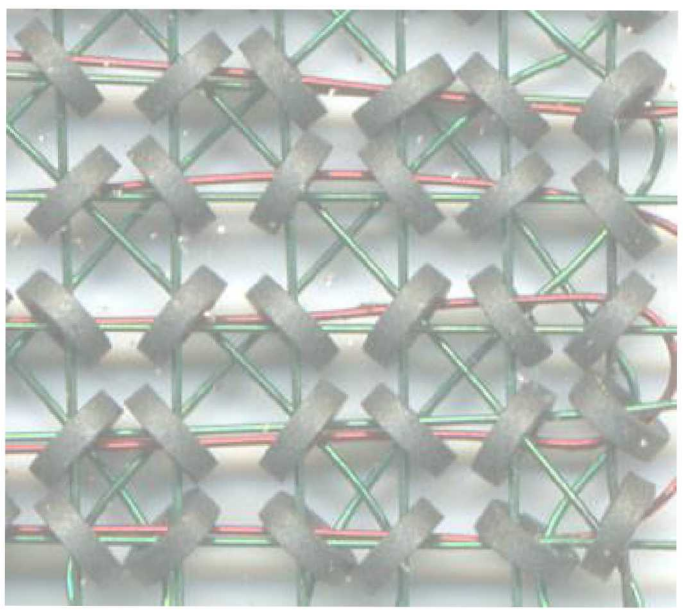
Qubits

Bits

Mercury Delay Line

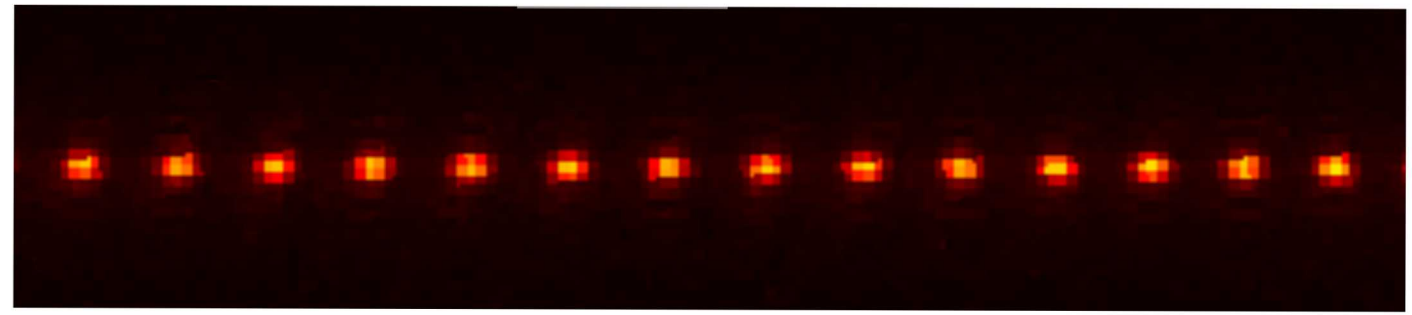


Magnetic Core

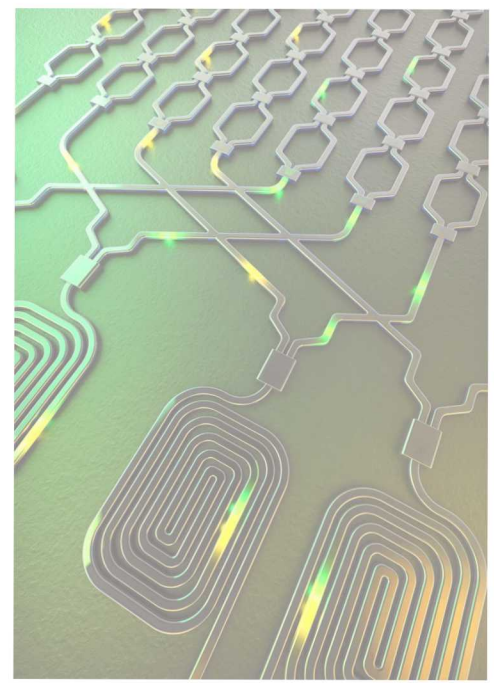


Qubits

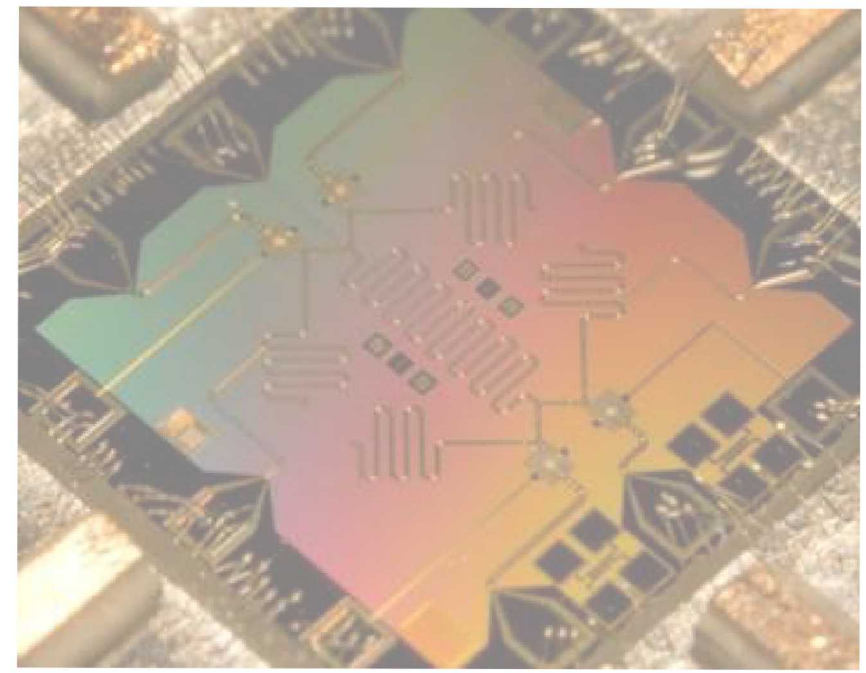
Atoms/ions

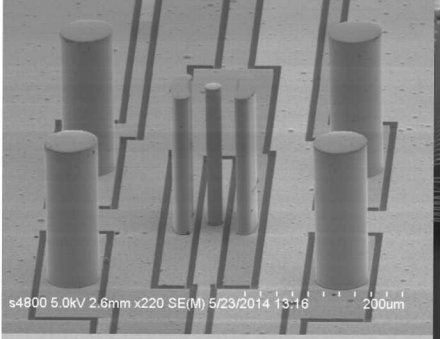


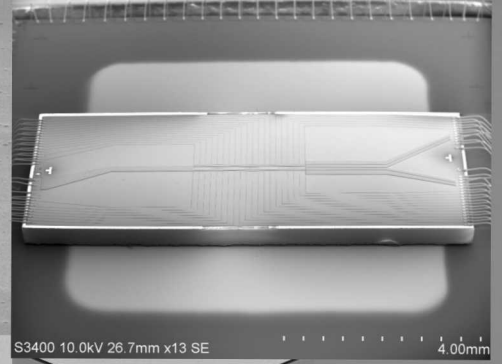
Photonic

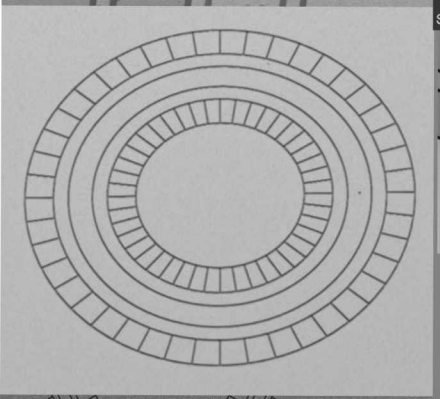


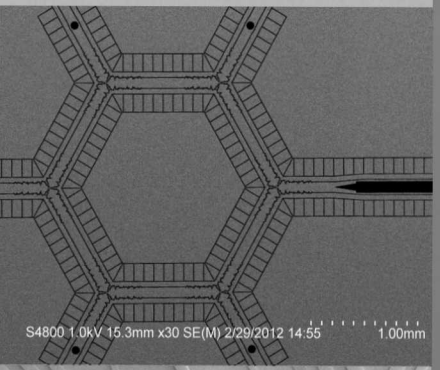
Superconducting

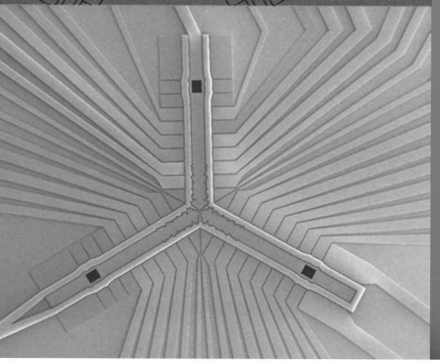


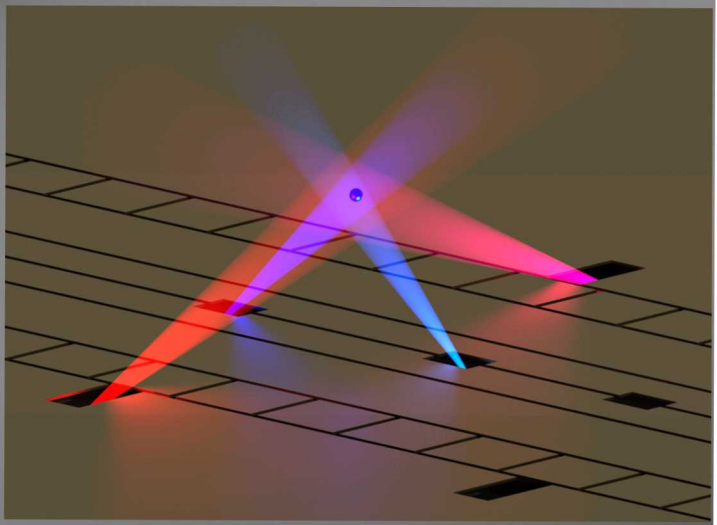






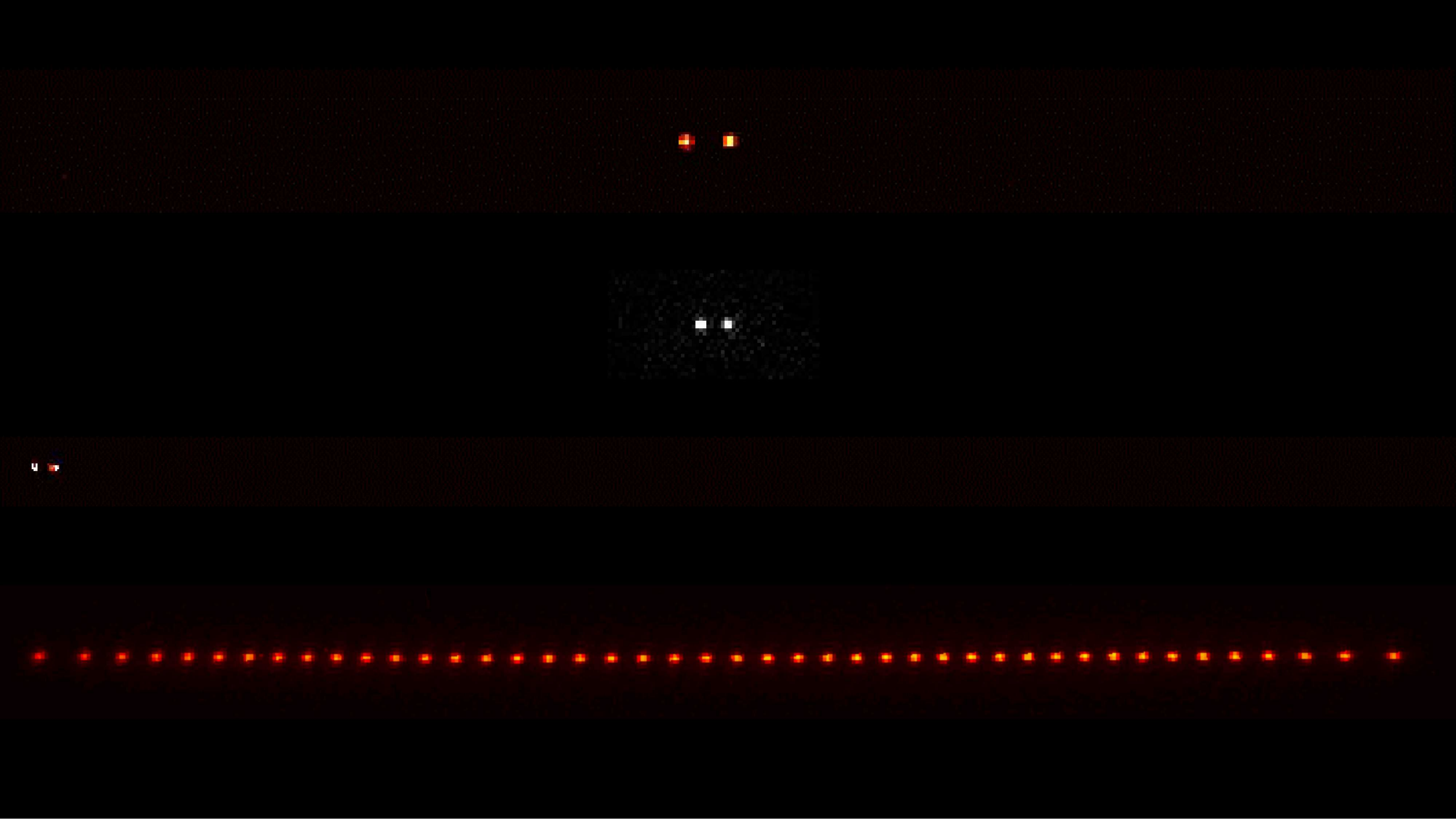




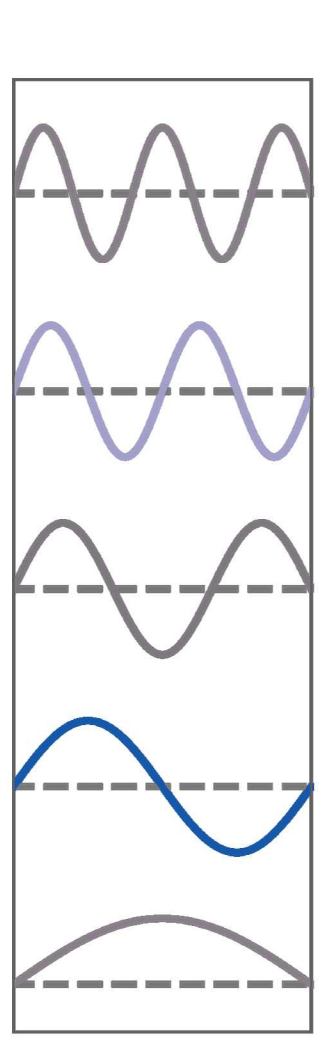


S3400 10.0kV 30.1mm x19 SE 3/30/2015

3.00mm



Frequency $\propto$ Energy



$|n\rangle$

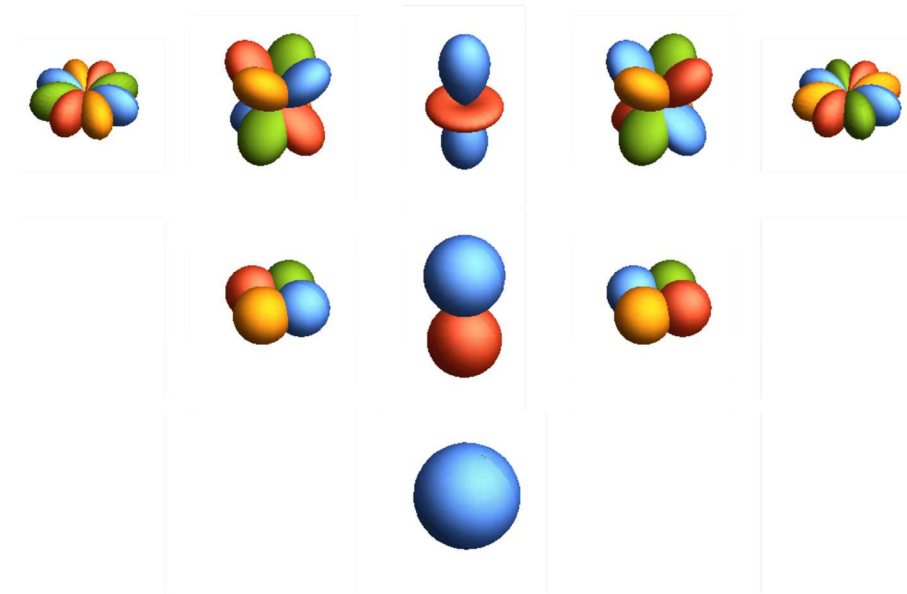
$|4\rangle$

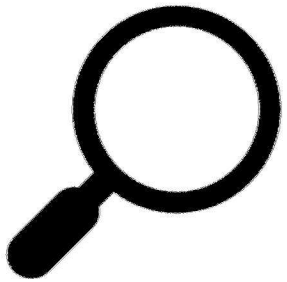
$|3\rangle$

$|2\rangle$

$|1\rangle$

$|0\rangle$





$^{171}Yb^+$

Energy

$^2P_{3/2}$

100 THz

$^2P_{1/2}$

$\gamma/2\pi = 19.6$ MHz

$\tau = 8.12$ ns

$^2S_{1/2}$

F=0

F=1

$\delta_{Zeeman} = 1.4$ MHz/G

12.642812118466 + δ_{2z} GHz

$\delta_{2z} = (310.8)B^2$ Hz [B in gauss]

2.105 GHz

$^3[3/2]_{1/2}$

$\gamma/2\pi = 4.2$ MHz

$\tau = 37.7$ ns

F=0

F=1

2.2095 GHz

$^2D_{3/2}$

$\gamma/2\pi = 3.02$ Hz

$\tau = 52.7$ ms

F=2

F=1

0.8 GHz

$^2D_{5/2}$

$\gamma/2\pi = 22$ Hz

$\tau = 7.2$ ms

F=2

F=3

$^1[5/2]_{5/2}$

F=2

F=3

$^2F_{7/2}$

$\tau = 5.4$ yrs

F=4

F=3

911 THz (98.8%)

811.28926 THz (405.64463 THz * 2) (99.5%)

222 THz (0.2%)

182 THz (1.0%)

123 THz (0.5%)

1009 THz (98.2%)

320.5 THz (1.8%)

88 THz (12%)

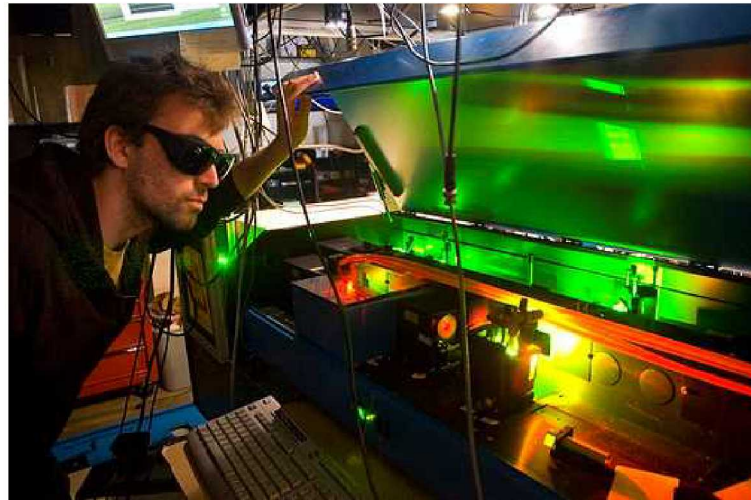
688.4 THz

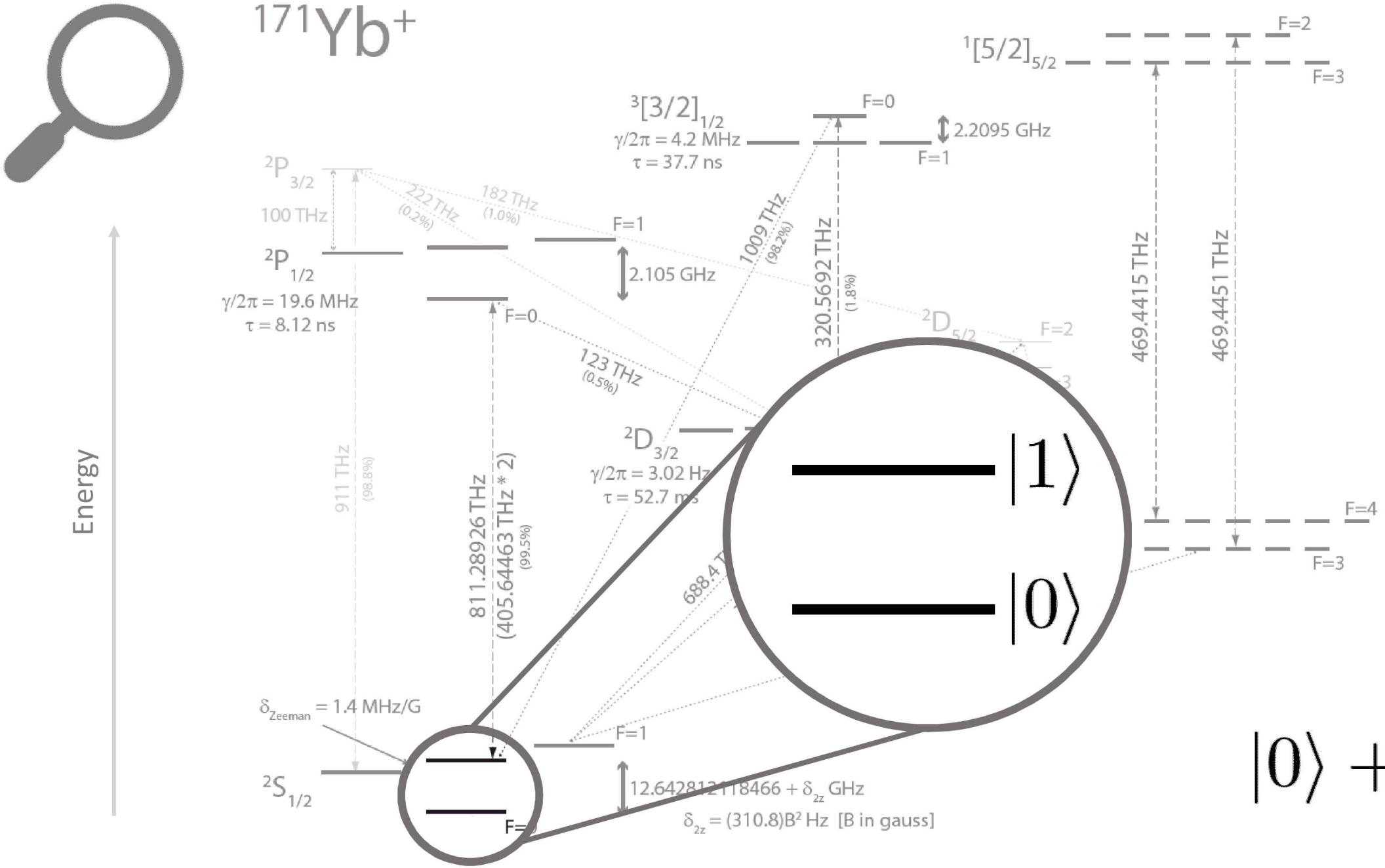
729 THz (17%)

642 THz

469.4415 THz

469.4451 THz

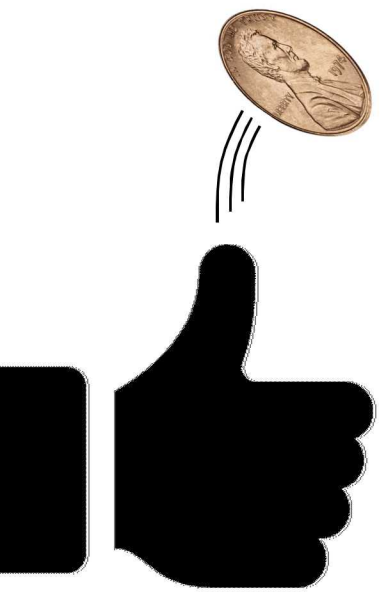




$$|0\rangle + |1\rangle \quad ?$$

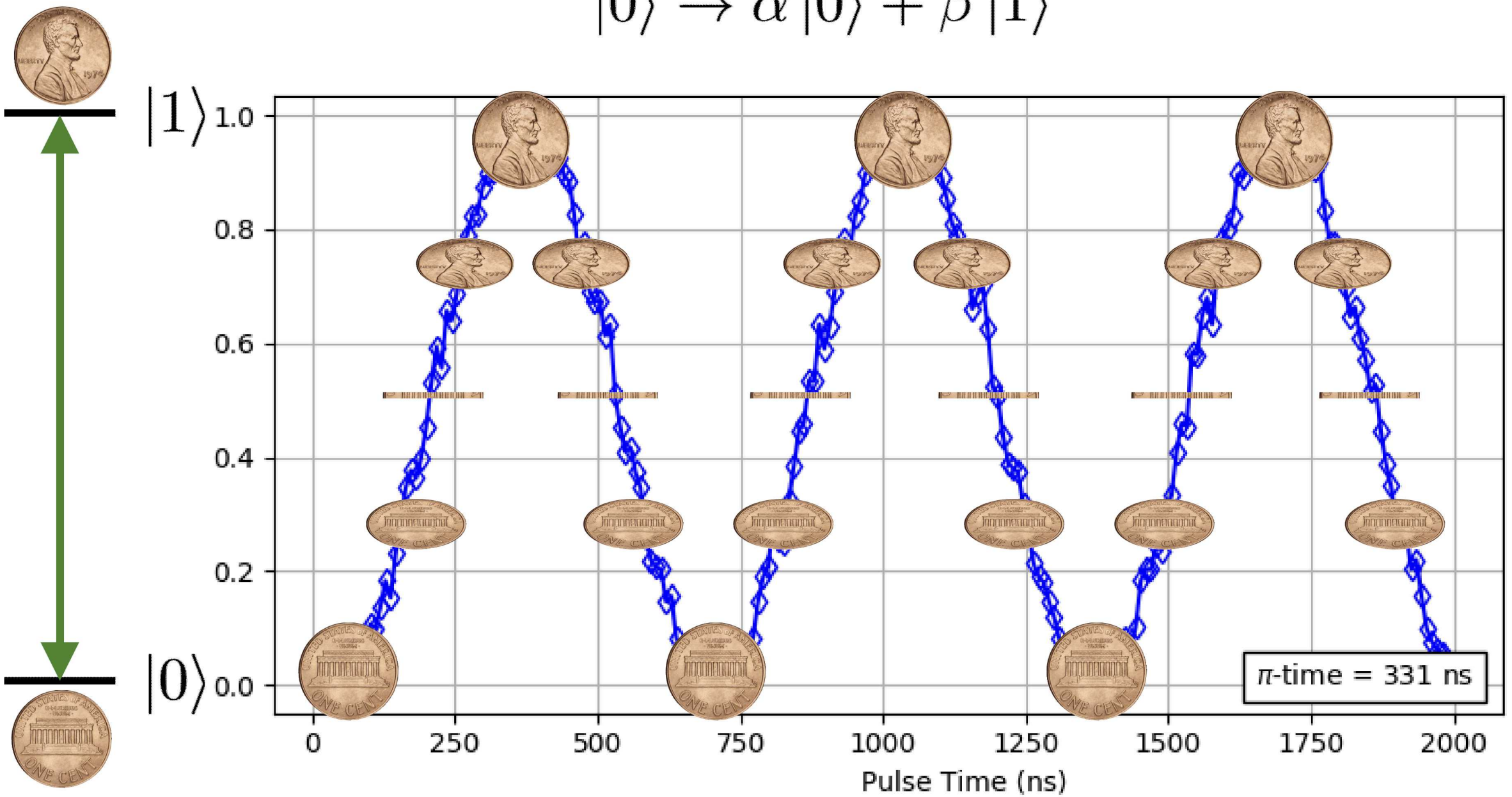
Quantum Superposition

$$\alpha |0\rangle + \beta |1\rangle$$

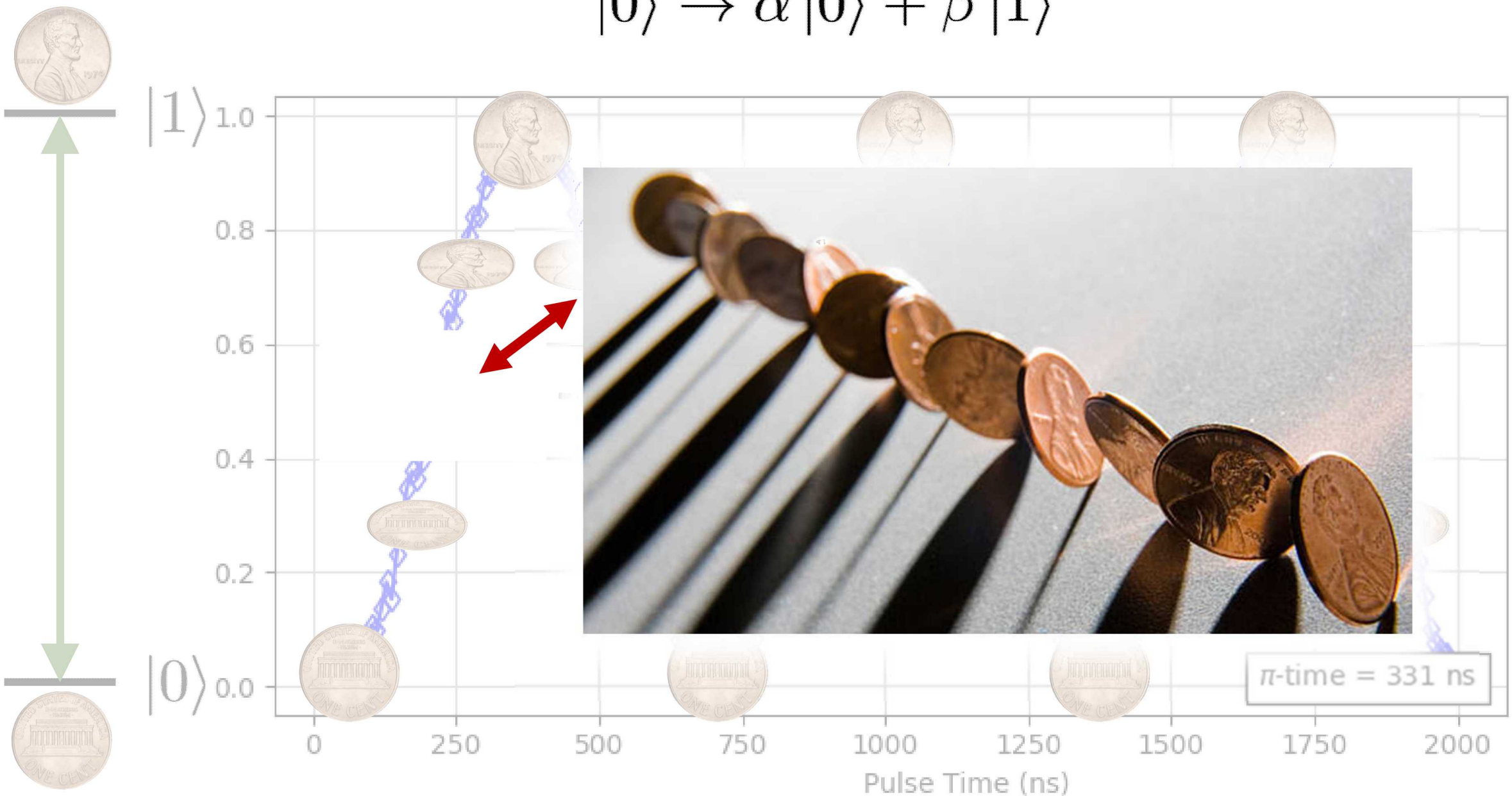


"Probability amplitude"
of measuring $|0\rangle$

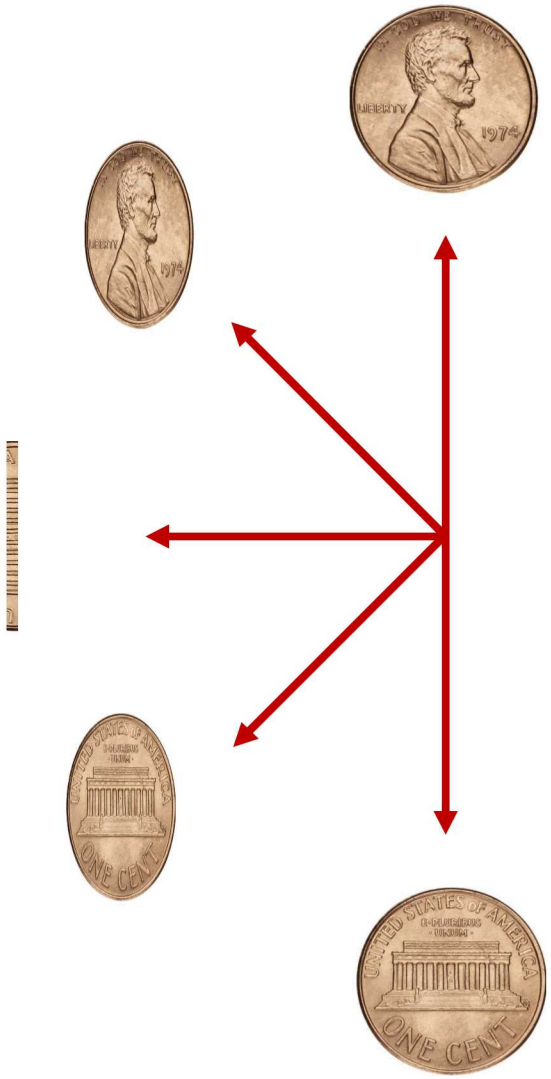
$$|0\rangle \rightarrow \alpha\,|0\rangle + \beta\,|1\rangle$$

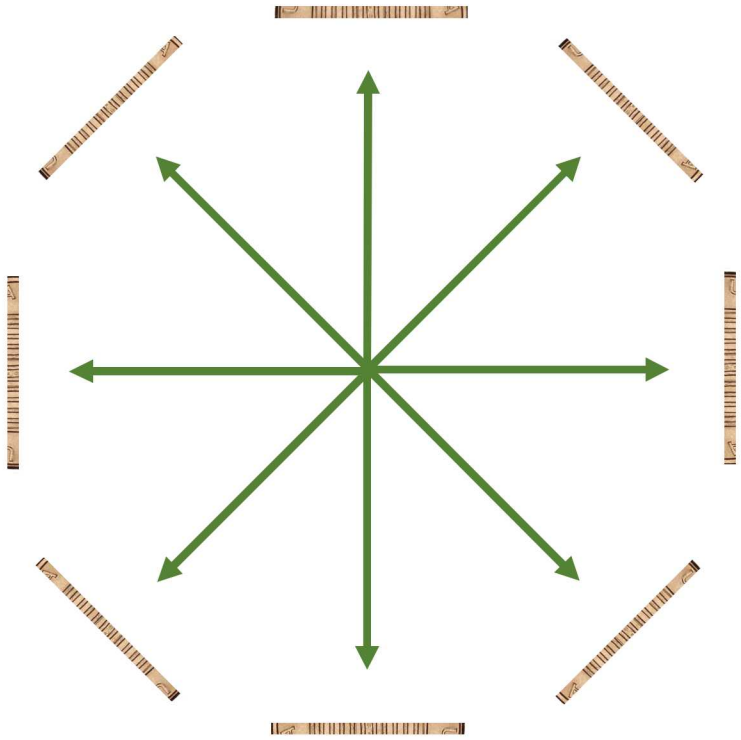


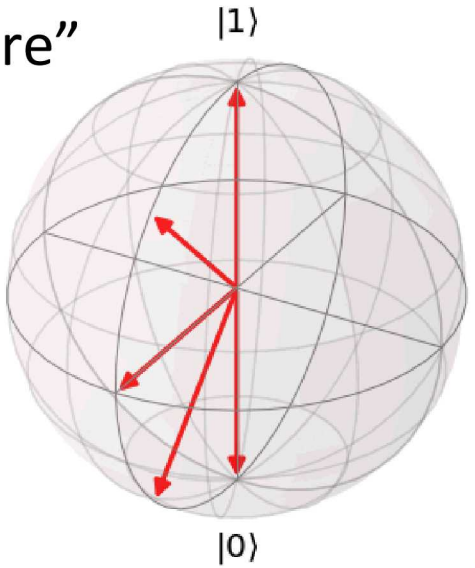
$$|0\rangle \rightarrow \alpha\,|0\rangle + \beta\,|1\rangle$$

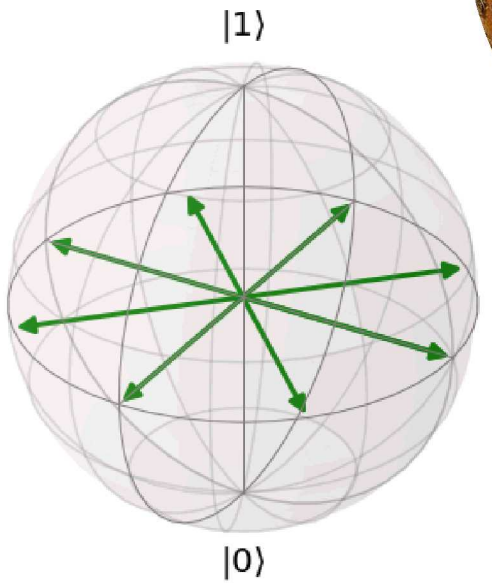


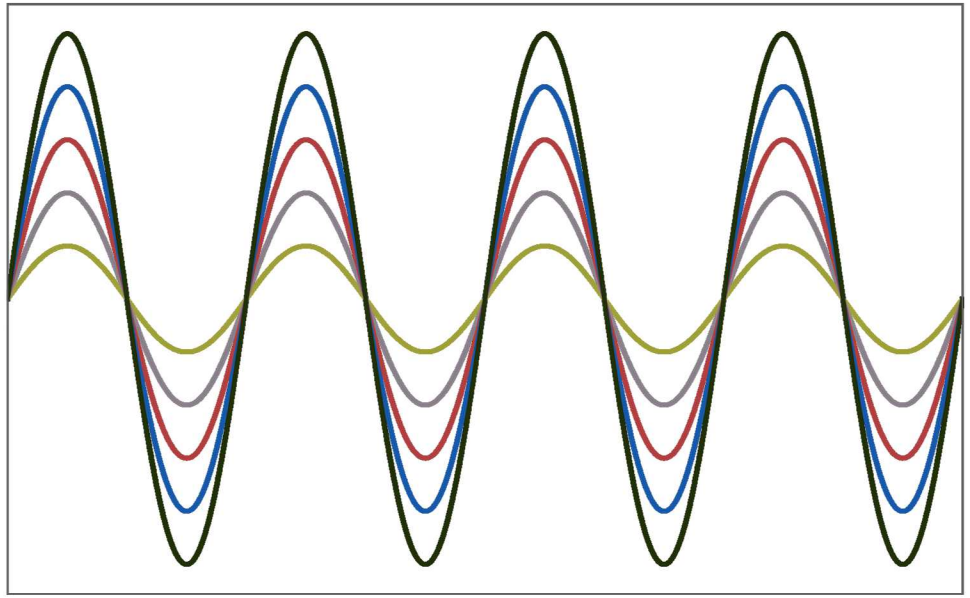
“Bloch Sphere”

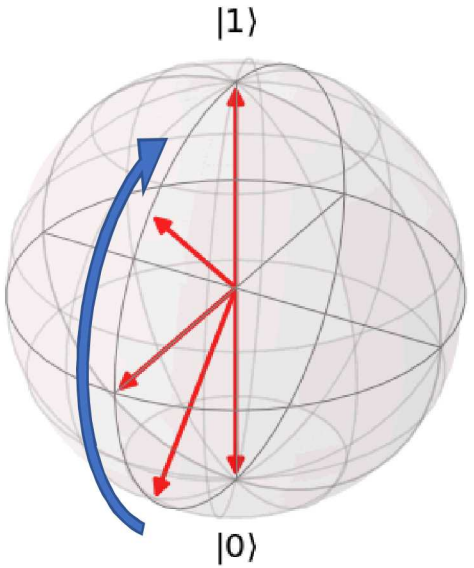




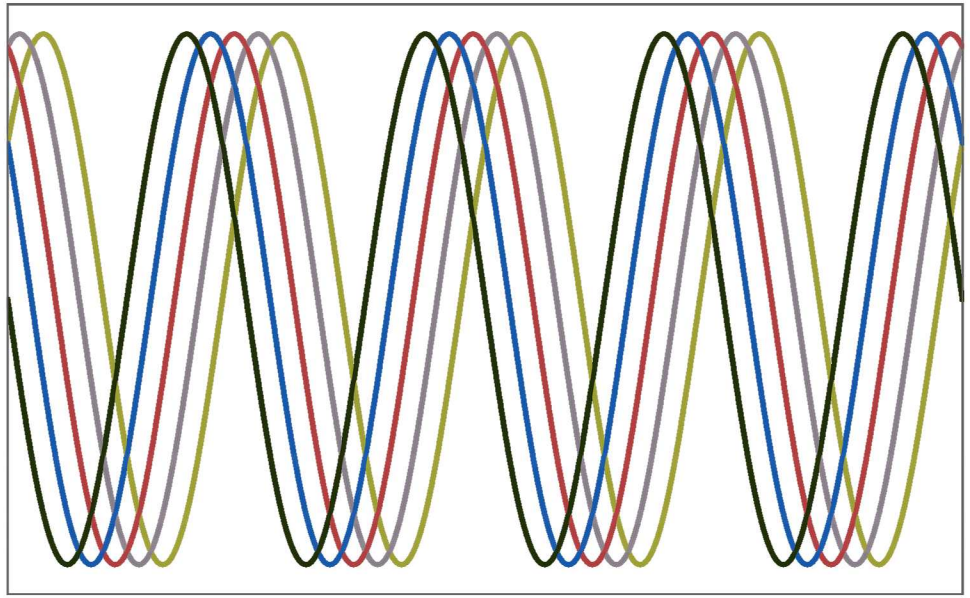


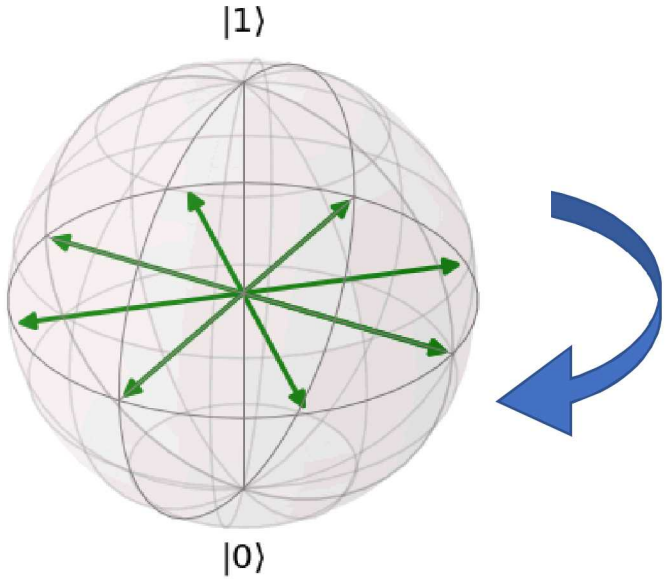




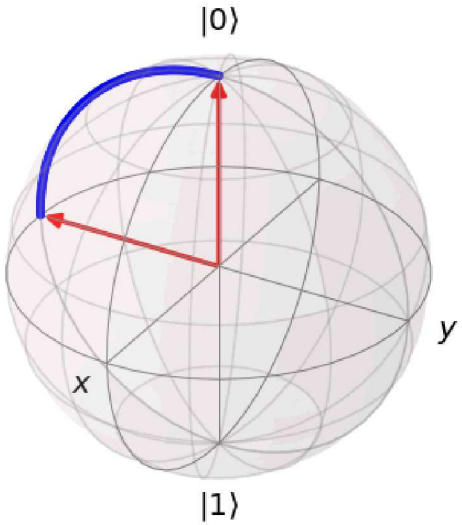


Laser beam intensity/duration

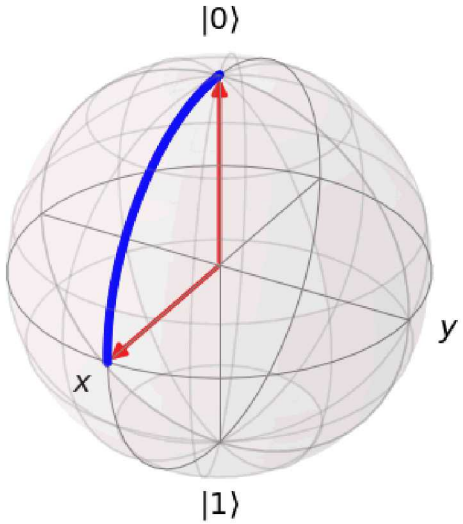




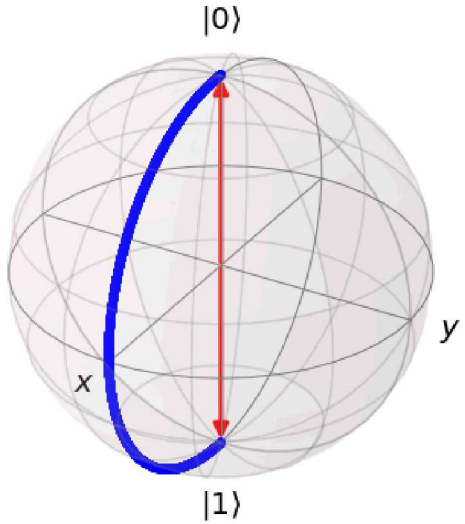
Laser beam phase



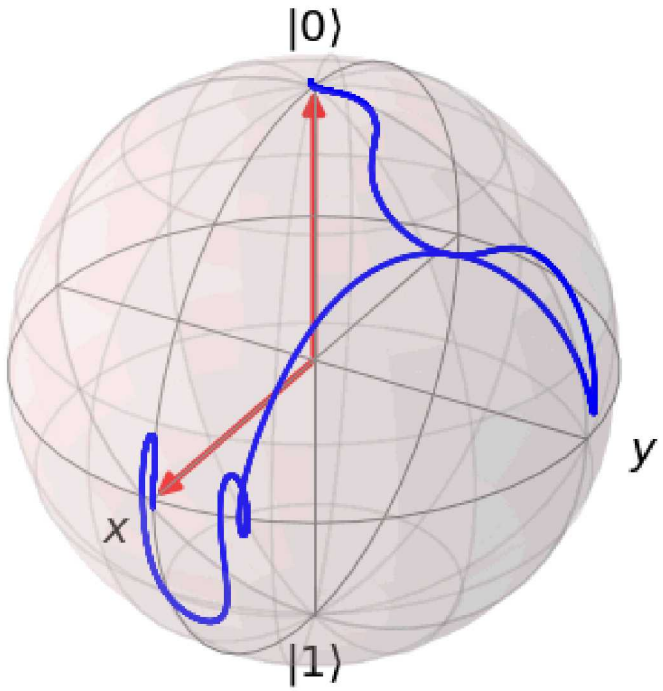
$R_x(\frac{\pi}{2})$

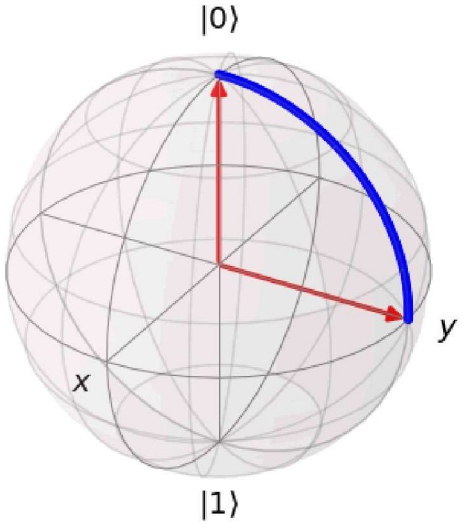


$R_y(\frac{\pi}{2})$

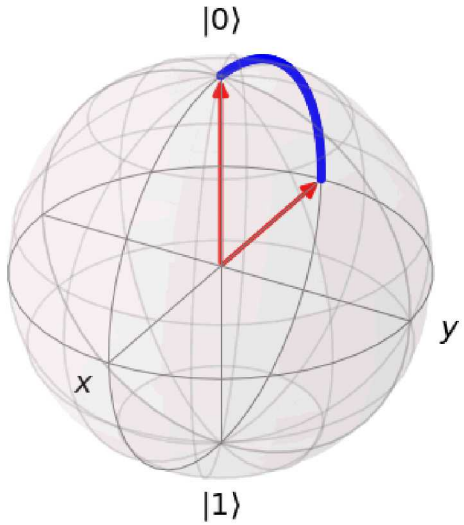


$R_y(\pi)$

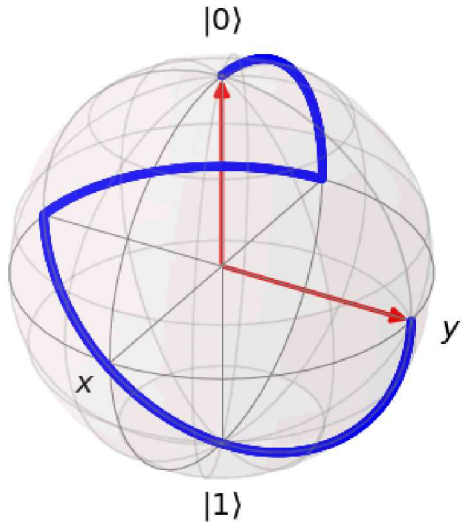




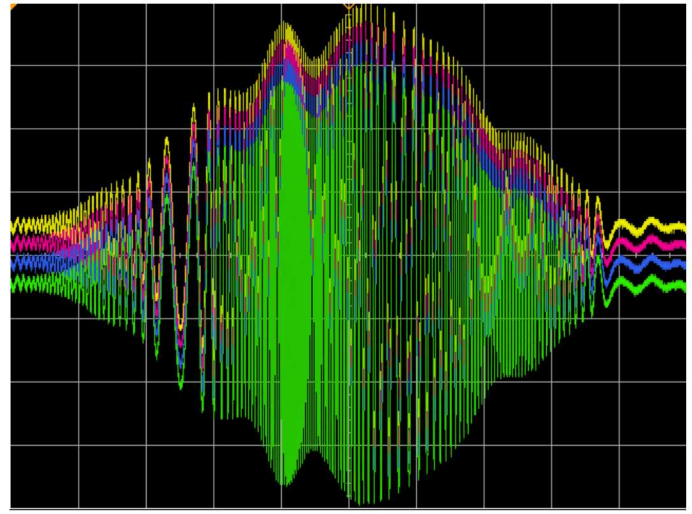
$R_x(-\frac{\pi}{2})$



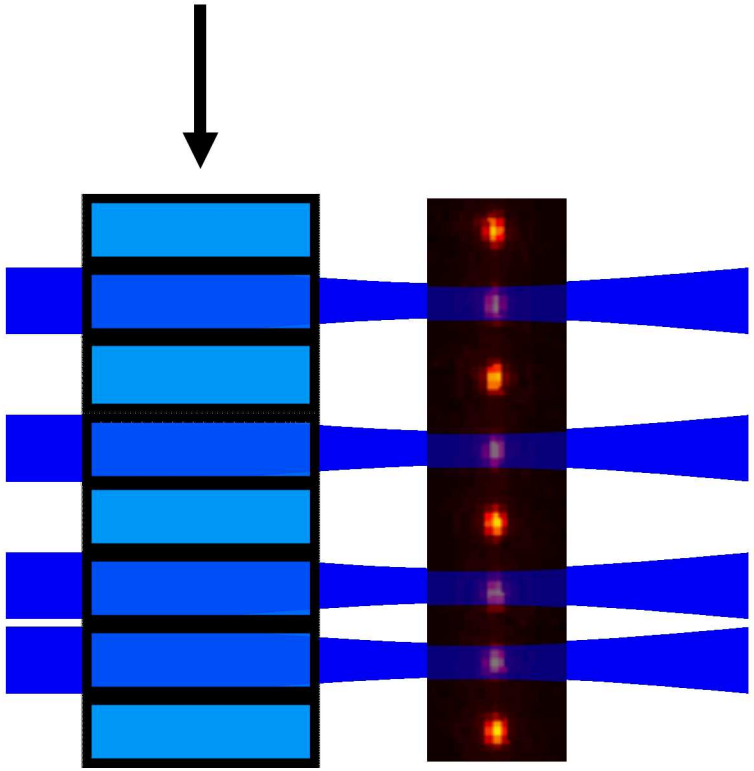
$R_y(-\frac{\pi}{2})$

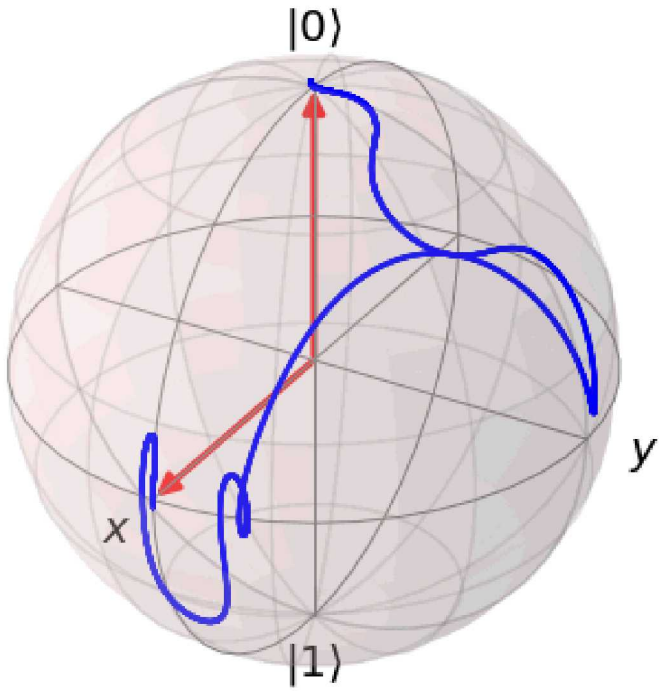


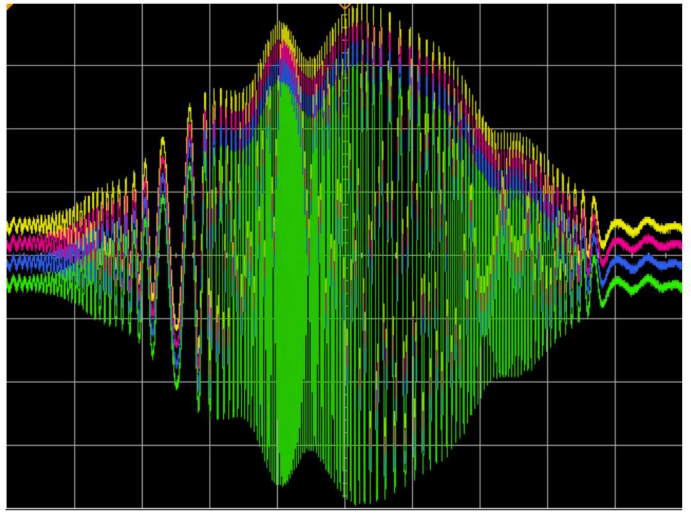
$R_x(\pi)R_z(\frac{\pi}{2})R_y(-\frac{\pi}{2})$



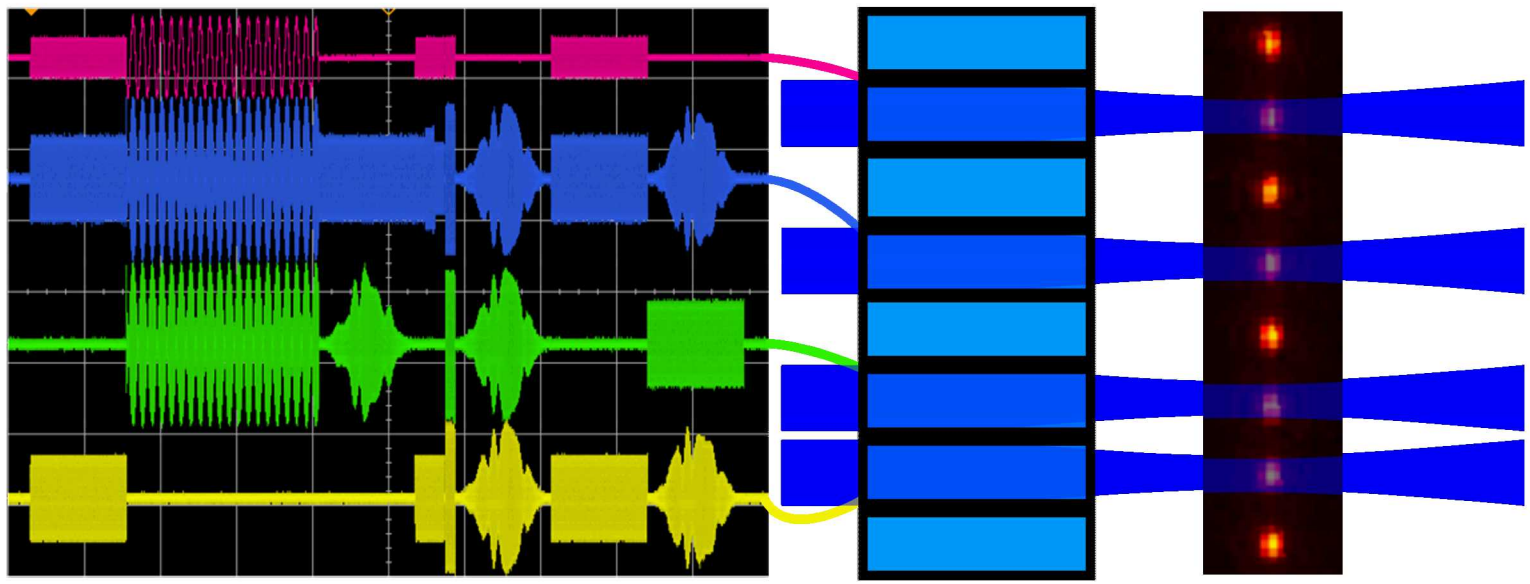
Acousto-Optic Modulators



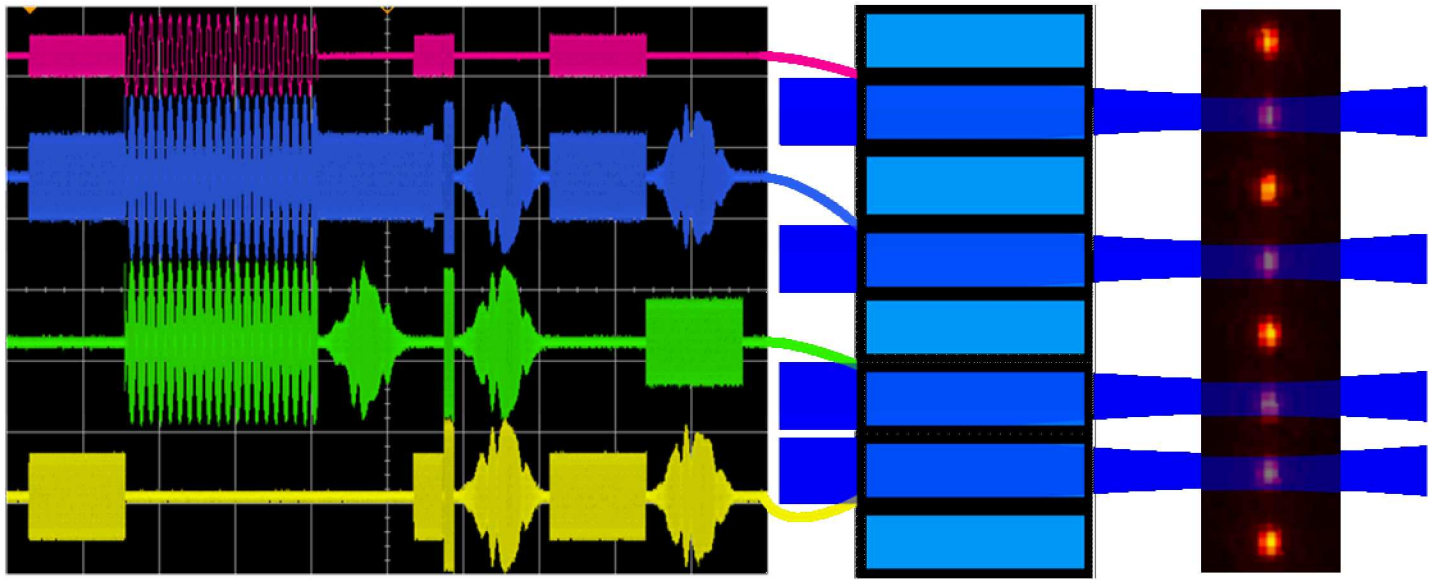


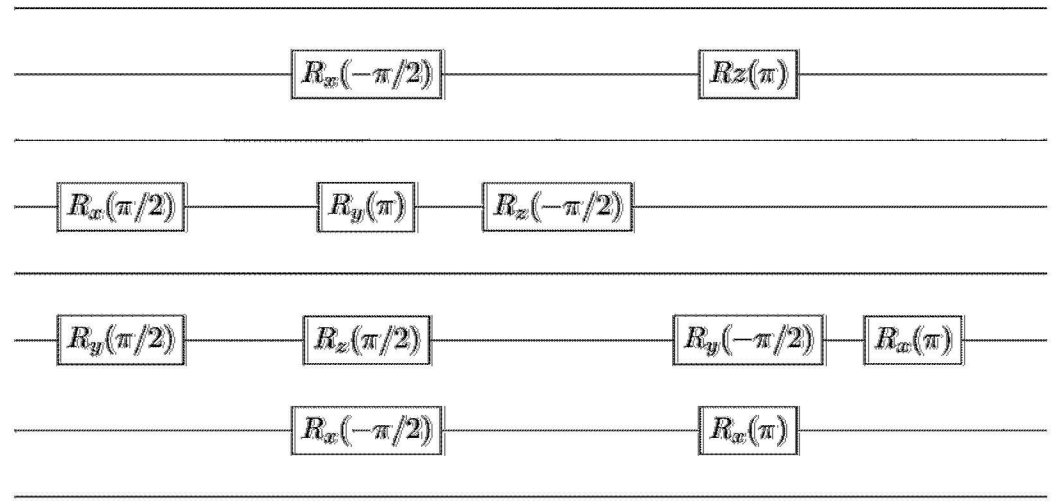


Acousto-Optic Modulators

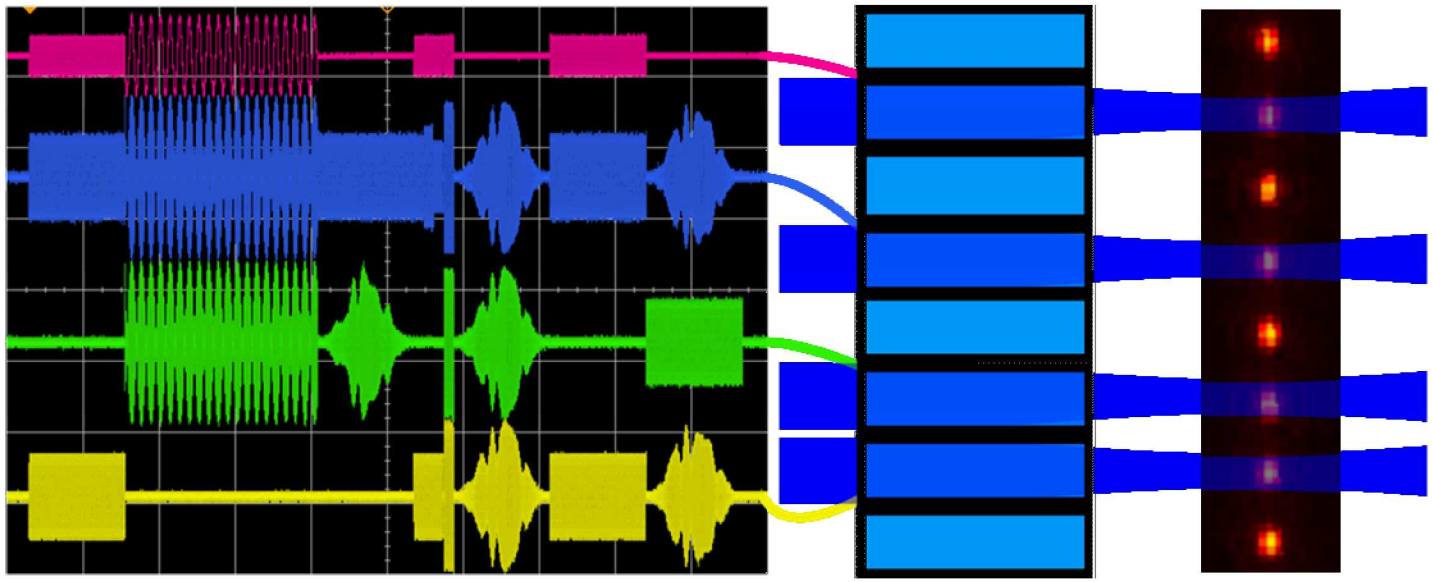


Acousto-Optic Modulators

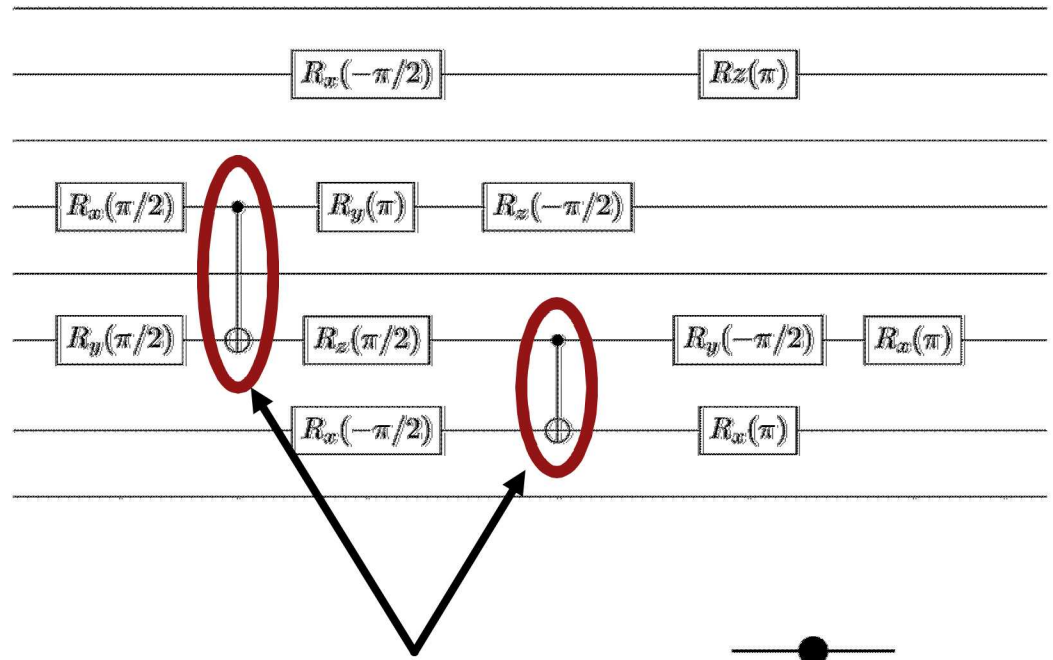




Acousto-Optic Modulators

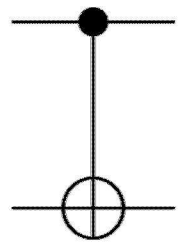


$$\text{CNOT} \begin{cases} |00\rangle \rightarrow |00\rangle \\ |01\rangle \rightarrow |01\rangle \\ |10\rangle \rightarrow |11\rangle \\ |11\rangle \rightarrow |10\rangle \end{cases}$$



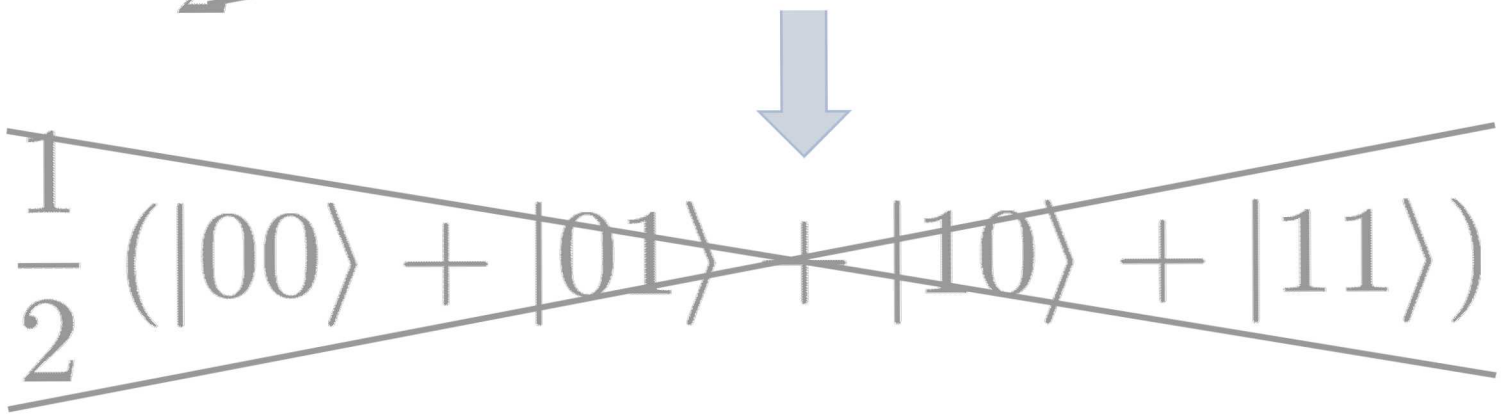
How can the state of one qubit effect change on another?

"Controlled NOT"
(CNOT)



Quantum Entanglement

$$\frac{1}{2}(|0\rangle + |1\rangle)(|0\rangle + |1\rangle)$$

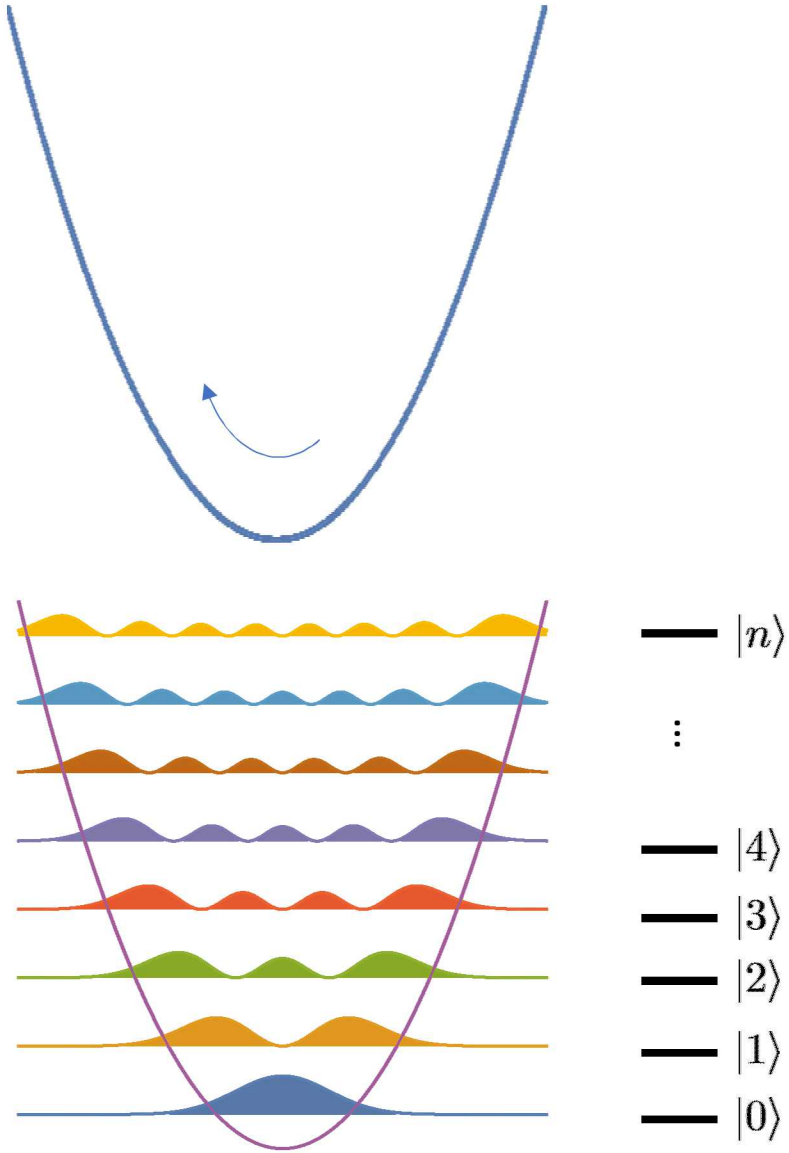


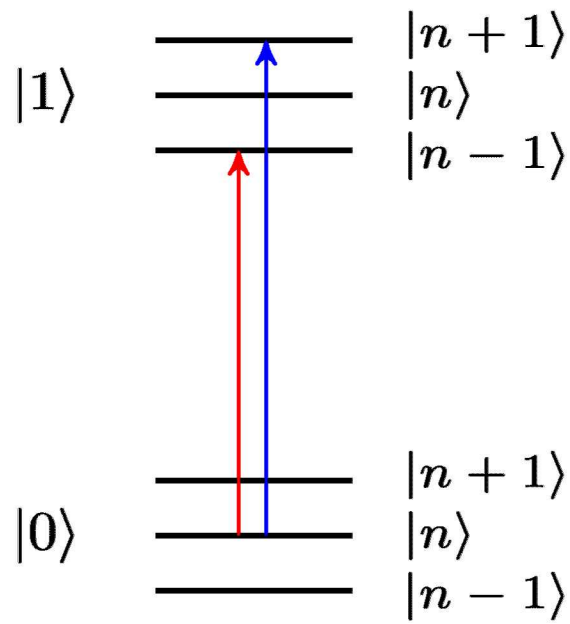
$$\frac{1}{2}(|00\rangle + |01\rangle + |10\rangle + |11\rangle)$$

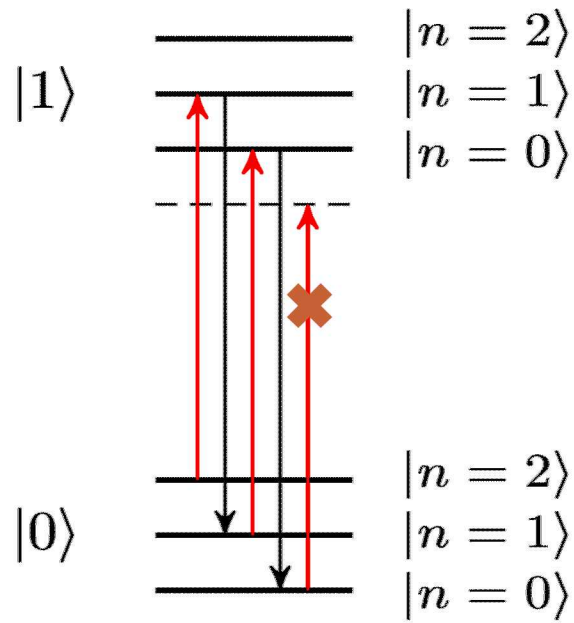
"Mixed State"

$$\frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

"Entangled State"

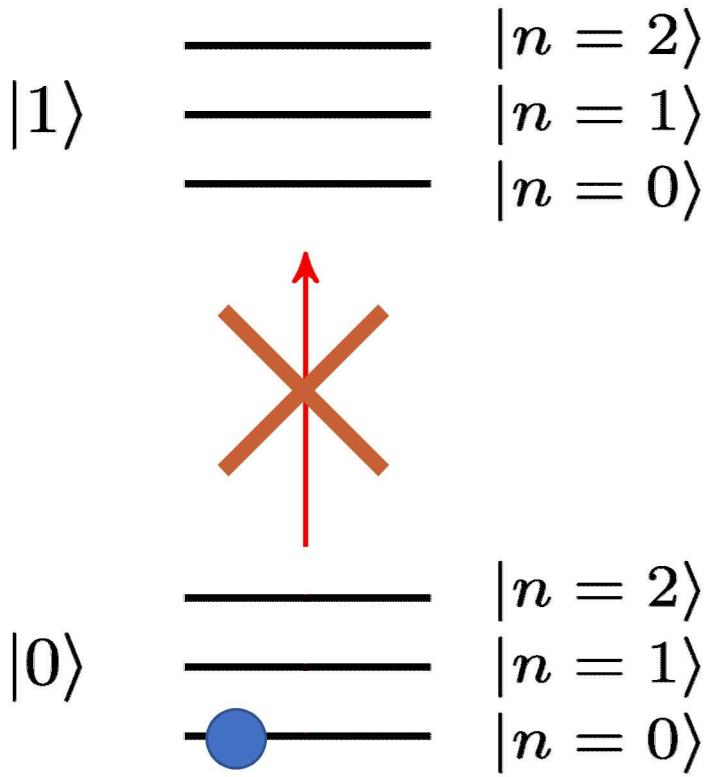

$|n\rangle$
$|4\rangle$
$|3\rangle$
$|2\rangle$
$|1\rangle$
$|0\rangle$


$|1\rangle$
$|n+1\rangle$
$|n\rangle$
$|n-1\rangle$
$|0\rangle$
$|n+1\rangle$
$|n\rangle$
$|n-1\rangle$


$|1\rangle$
$|n=2\rangle$
$|n=1\rangle$
$|n=0\rangle$
$|0\rangle$
$|n=2\rangle$
$|n=1\rangle$
$|n=0\rangle$

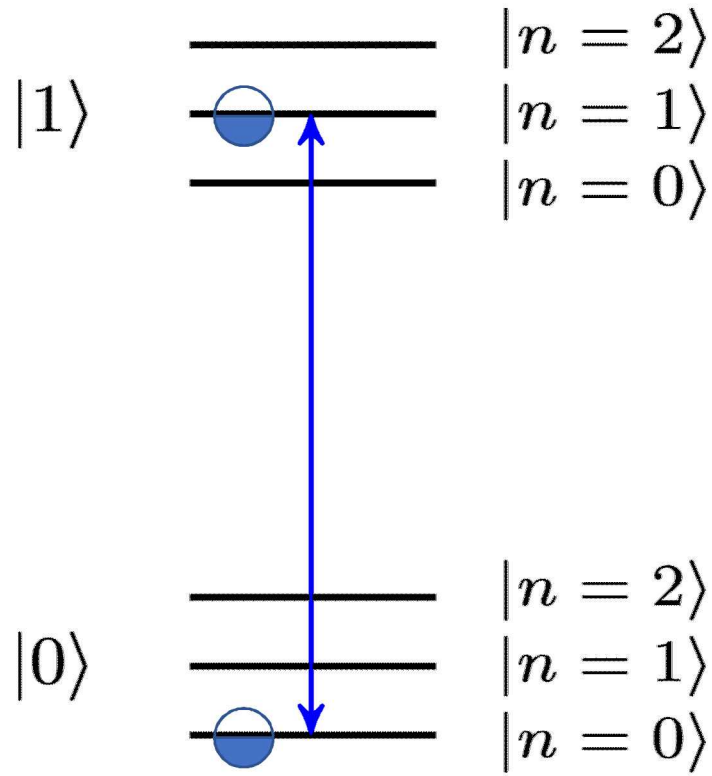
No change!

$$|0,0\rangle \rightarrow |0,0\rangle$$

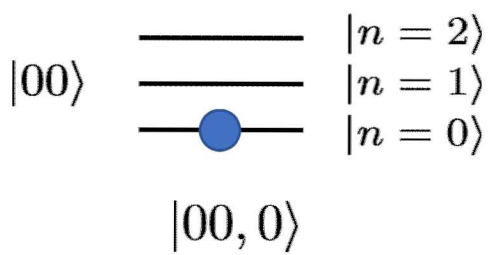


Qubit state entangled with its motion!

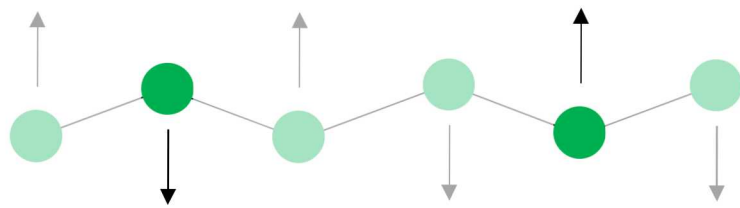
$$|0,0\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|0,0\rangle + |1,1\rangle\right)$$



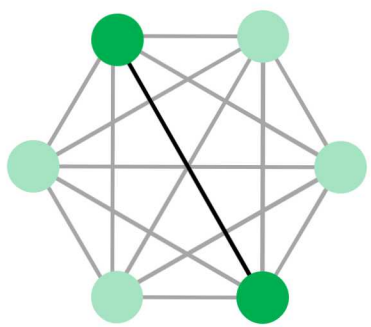
How do we entangle 2 qubits?

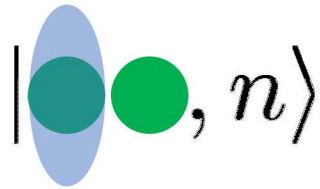


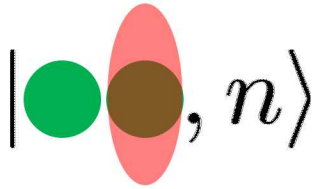
Ions “share” motion!



“Fully connected”

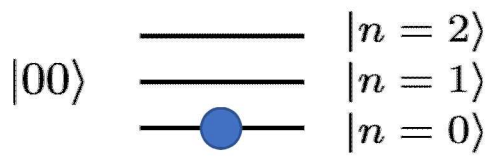




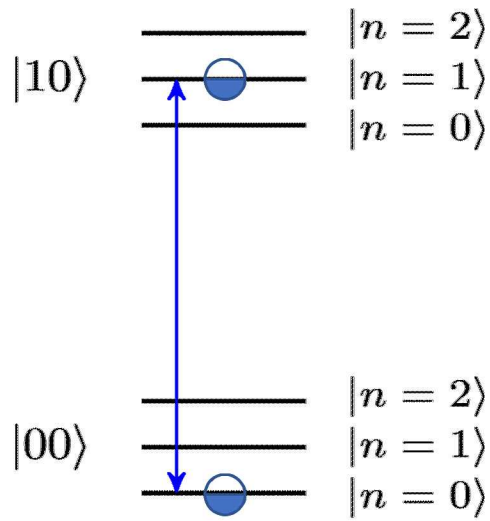


$$|00,0\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|00,0\rangle + |11,0\rangle\right)$$

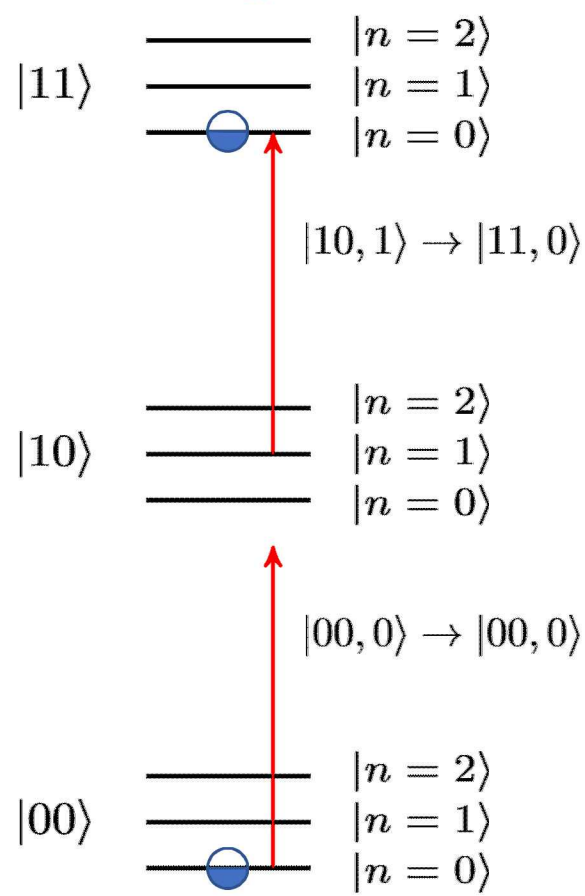
$$|00\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|00\rangle + |11\rangle\right)$$



$|00,0\rangle$



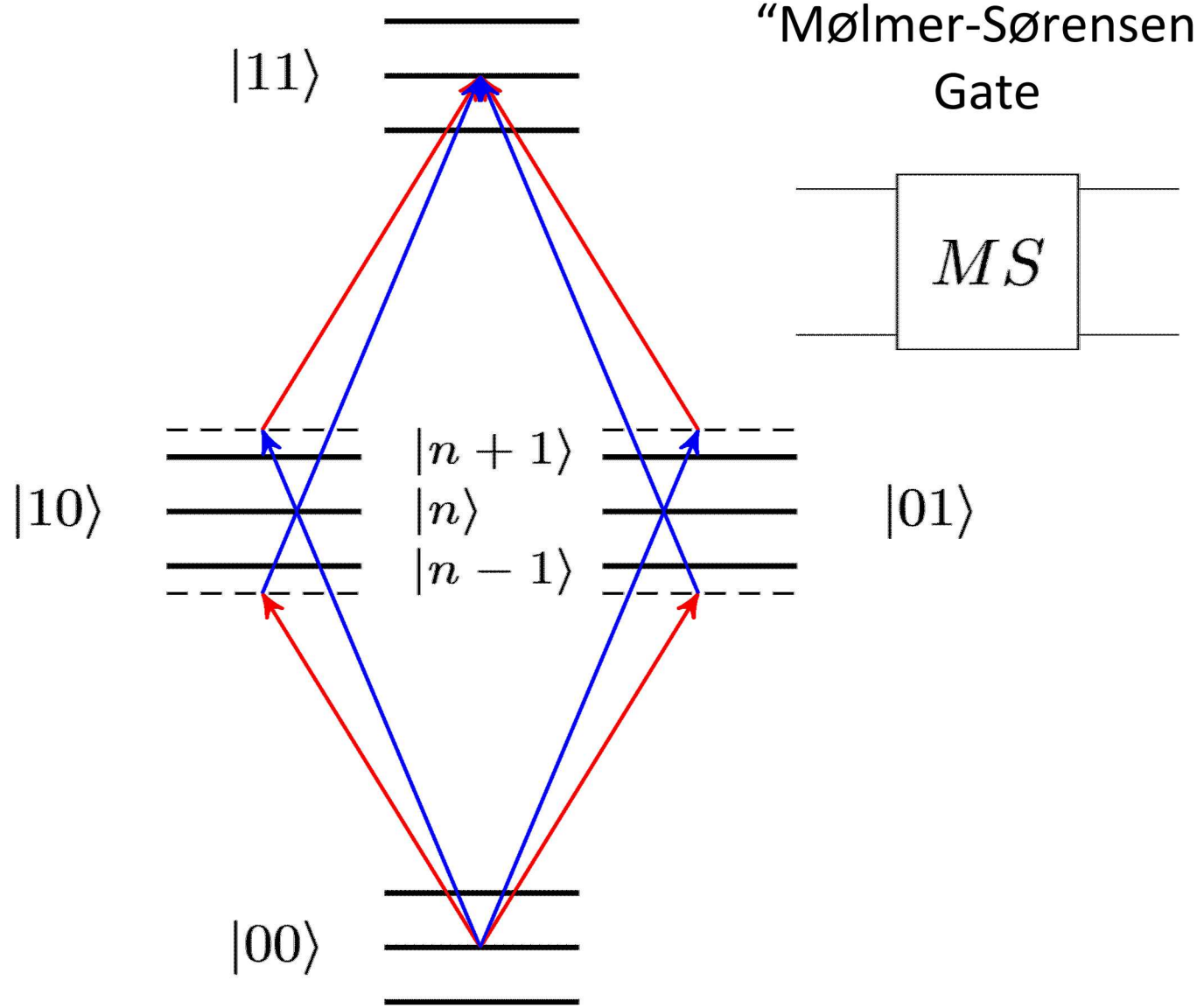
$$\frac{1}{\sqrt{2}}\left(|00,0\rangle + |10,1\rangle\right)$$



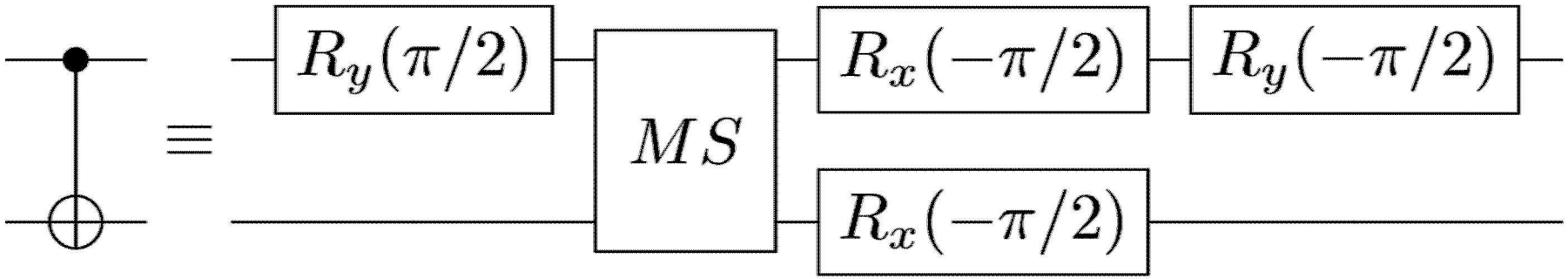
$$\frac{1}{\sqrt{2}}\left(|00,0\rangle + |11,0\rangle\right)$$

“Mølmer-Sørensen” Gate

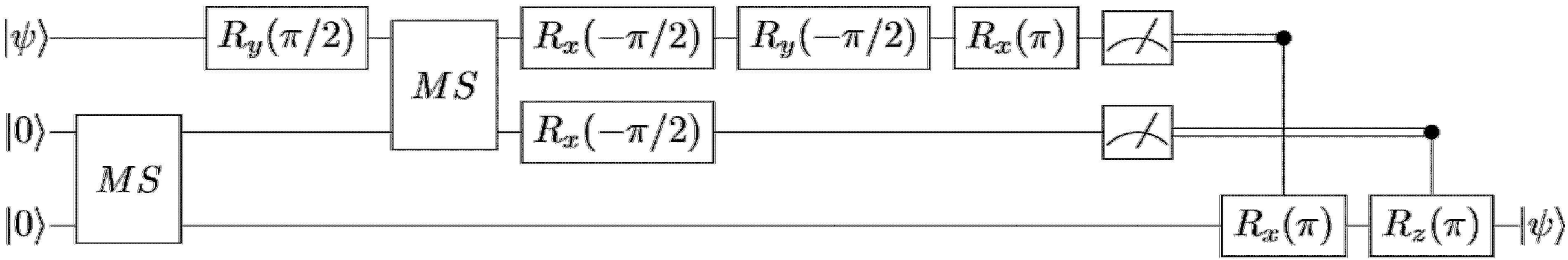
$$|00\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|00\rangle + |11\rangle\right)$$



Controlled NOT Gate



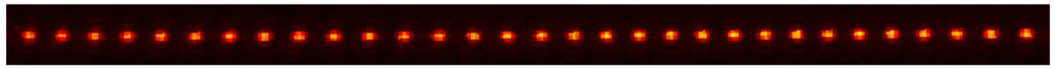
Quantum Teleportation



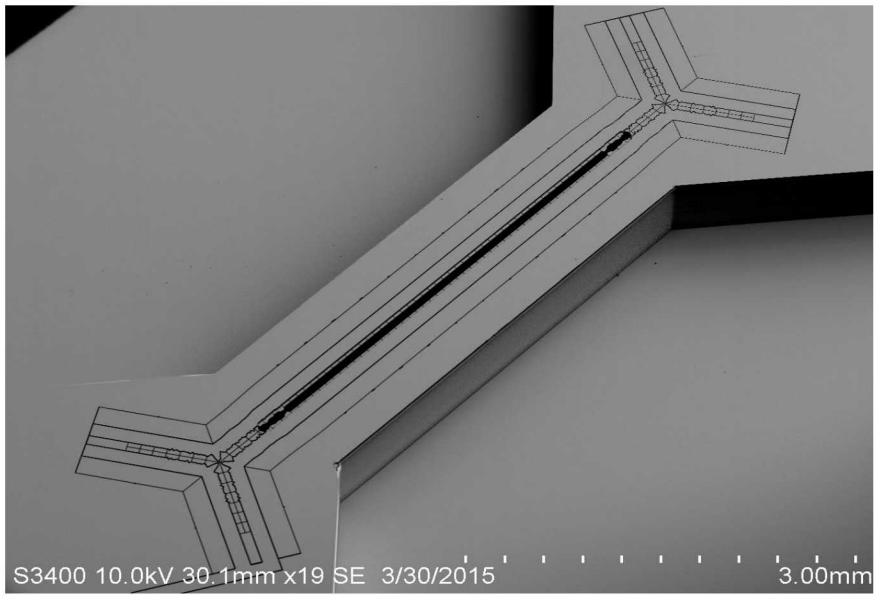
Summary

Qubits

- **Ions**, naturally-occurring, identical, near-ideal source for robustly storing quantum information



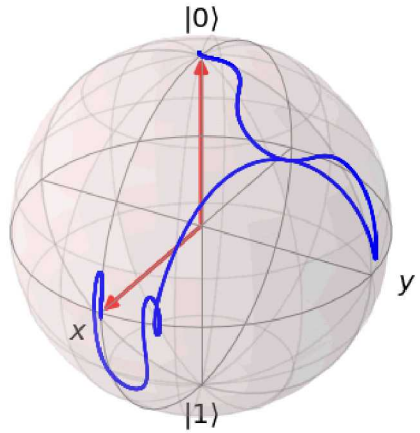
- **Trapped by electric fields** in *scalable* microfabricated traps

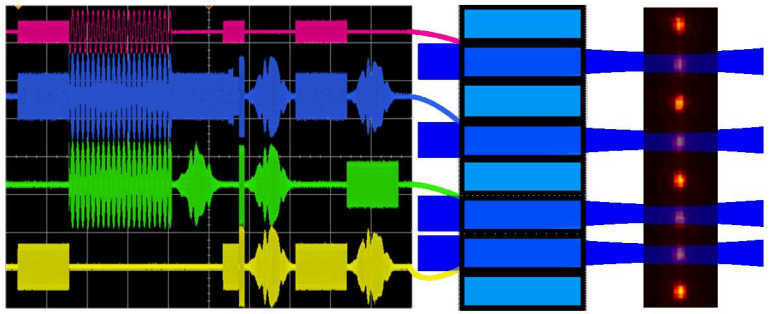


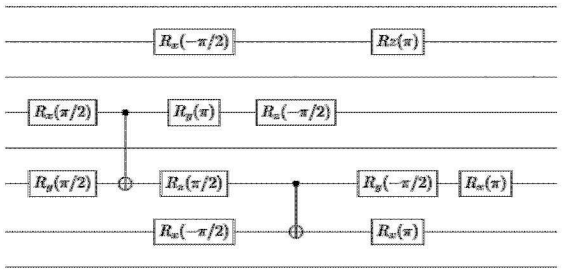
Quantum Gates

Quantum Superposition

- Used for **single-qubit gates**
- Precisely controlled by **manipulating laser light** via radiofrequency waves



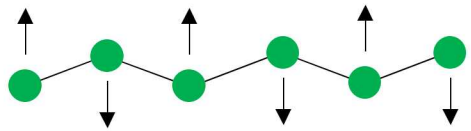




Quantum Entanglement

$$\frac{1}{\sqrt{2}}\left(|00\rangle + |11\rangle\right)$$

- Quantum **states are correlated**
- **Mediated by interactions** between ions



- Enables **two-qubit gates** & more exotic aspects of quantum information (e.g. “superdense” coding and teleportation)