ACM Winter School on Quantum Computing

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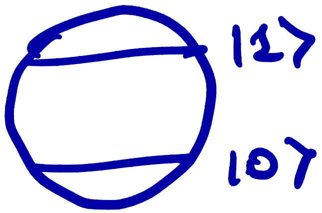
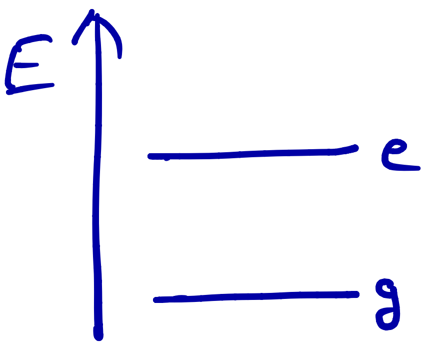


$\alpha|0\rangle + \beta|1\rangle$.

qubit $\longleftrightarrow$ classical bit

$\{0, 1\}$



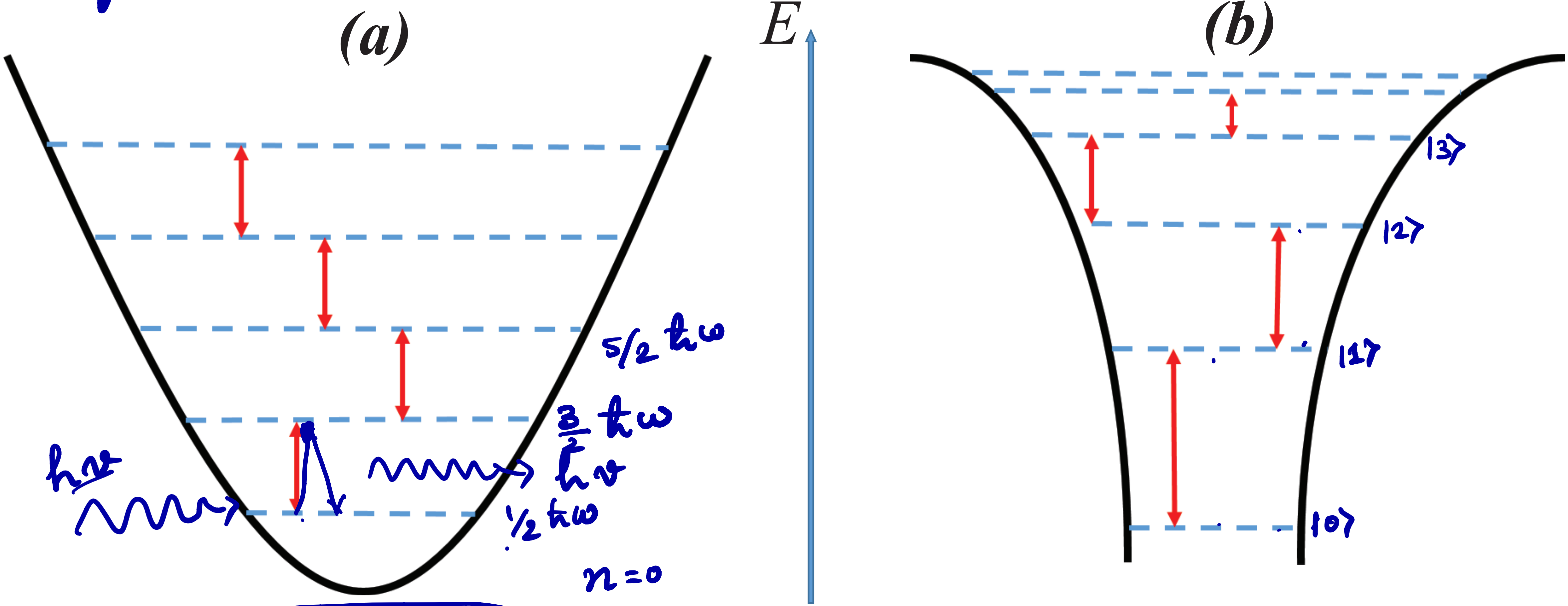
transition

superposition

$H = x^2 + p^2$

quantum Harmonic oscillator

Atom $E = -1/n^2$



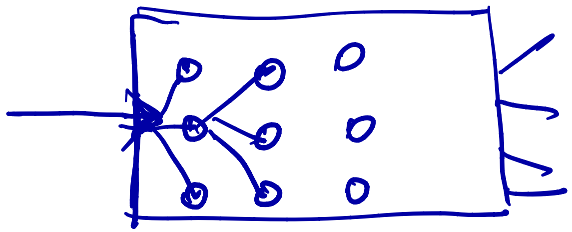
$E = (n + 1/2)\ \hbar\omega$

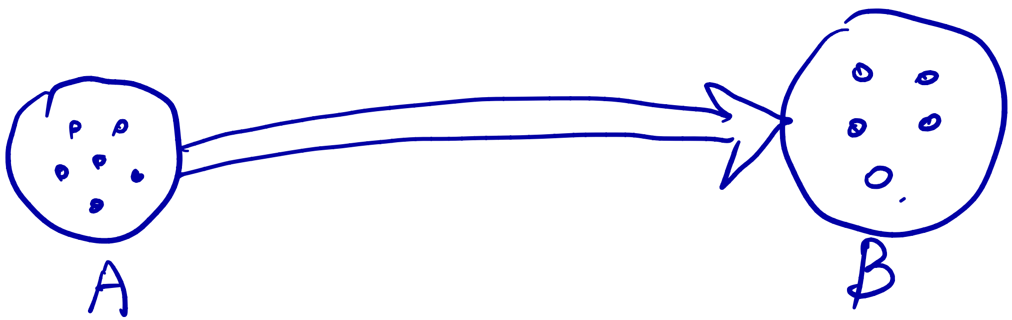
$E = -\ 1/n^2$

qubit

Stationary qubit

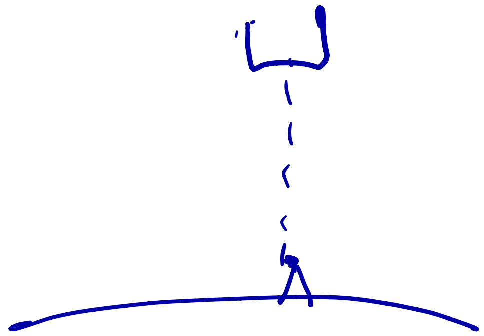
1. NMR qubits
2. Diamond NV center
3. Ion trap
4. Superconductor qubits





Flying qubits

1. Photonic qubits



qubit → Physical degree of Freedom → Spin → Electron spin

Nuclear spin

→ Polarization

→ Phase

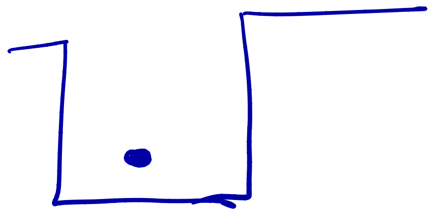
→ Charge, flux, phase

↓

qubit levels

Di vincenzo's Criteria:

quantum dots → Semiconductor qubits



Divincenzo's Criteria

1. Scalability :

IBM → 8
IBM → 20
IBM → 127

2. Initializing to a simple fiducial state :

$|0\rangle$ —

$|1\rangle$ —

$|0\rangle$ — 1

$|1\rangle$ — 2

3. Long decoherence time.

Physical → qubit

→ quantum in nature

$T_1 \rightarrow$ thermal relaxation time

- Time needed for the qubit $|e\rangle \xrightarrow[T_1]{} |g\rangle$.

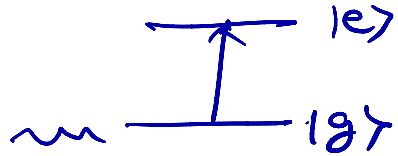
$|e\rangle\langle e|$

- $\rho = \alpha |e\rangle\langle e| + \beta |g\rangle\langle g|$

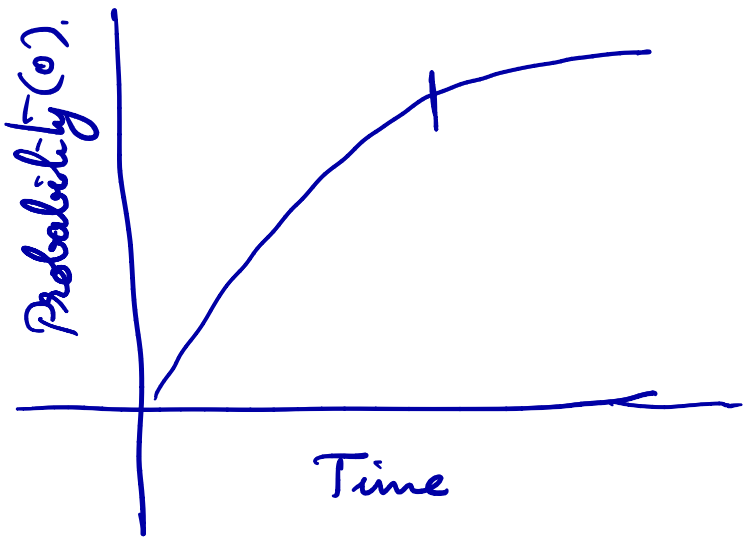
  $\alpha^2 \rightarrow$ probability of being in $|e\rangle$

  $\beta^2 \rightarrow$ probability of being in $|g\rangle$.

  $\beta^2 = 1$.



- Prepare the qubit in the excited state.
- Wait 't'
- Measure the state of the qubit.



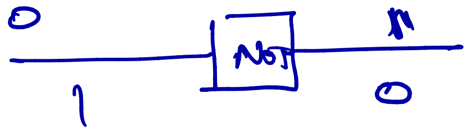
$T_1 \rightarrow 1/e$

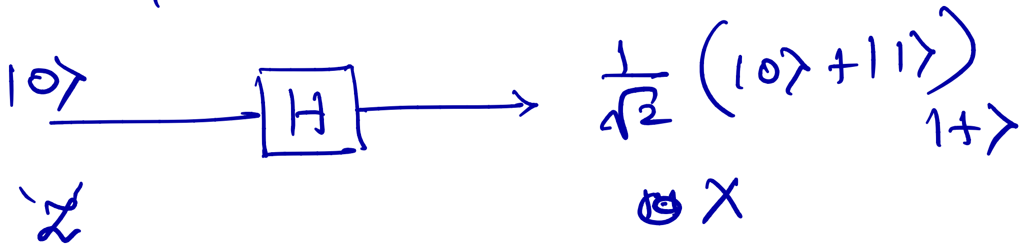
$T_2 \rightarrow$ Dephasing time

$\downarrow$

time taken for the loss of coherence.

4. Implementing Universal set of Quantum gates

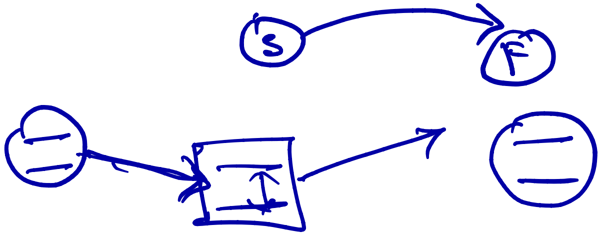




5. Qubit specific measurement capability

1. Ability to interconvert stationary & Flying qubit

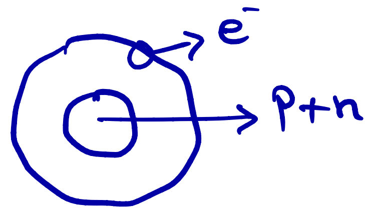
2. Ability to transmit Flying qubit



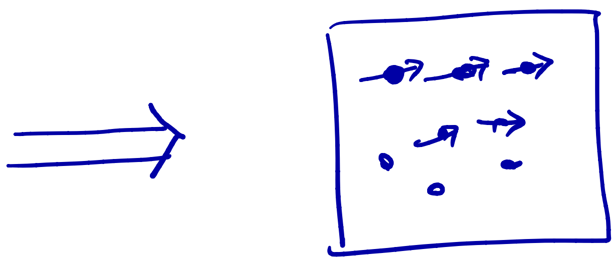
NMR Qubit

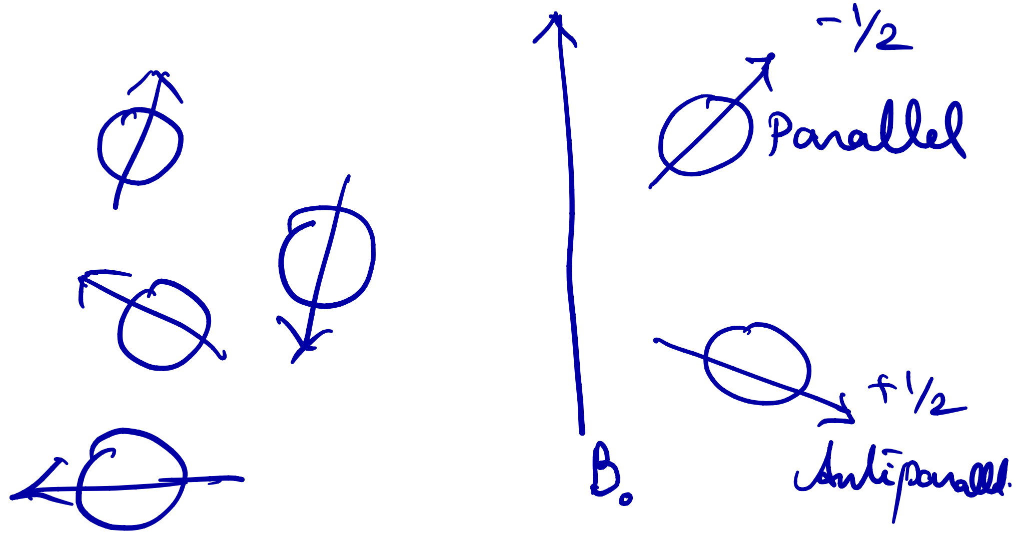
↓

Nuclear magnetic Resonance (Nuclear spins)



^{1}H $\quad$ ^{13}C $\quad$ ^{15}N $\quad$ ^{19}F $\quad$ ^{31}P





Spin-spin coupling interaction

+

NMR Pulses

two qubit gate rotations

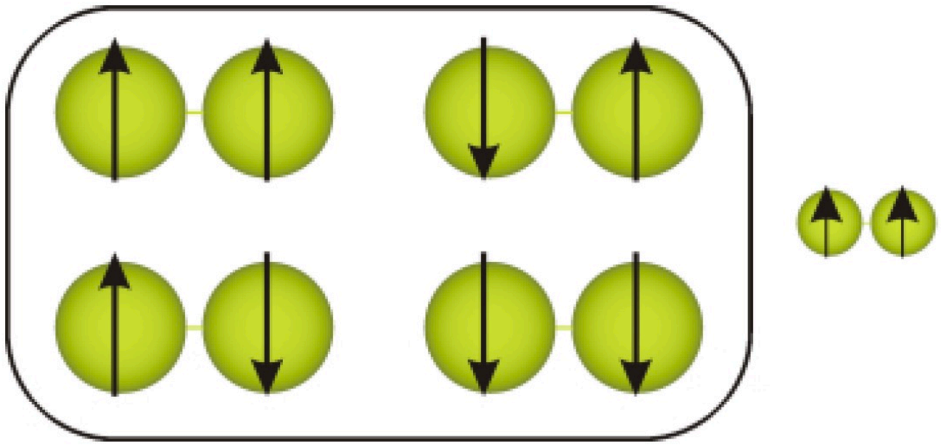


Fig. 4 A pseudo-pure state of a two qubit system. There are nearly equal populations of the four spin eigenstates, and these do not contribute to the overall spectrum; only a signal from the small excess population is seen.

$|0\rangle |0\rangle = |00\rangle$

$\rho = (1-\varepsilon)\frac{\mathbb{1}}{4} + \varepsilon |00\rangle\langle 00|$

$|00\rangle$
$|01\rangle$
$|10\rangle$
$|11\rangle$

$\varepsilon = 1.$

$\rho = 1\,|00\rangle\langle 00| \Rightarrow |\psi\rangle = |00\rangle$

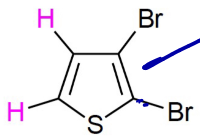
$\varepsilon = 0$

$\rho = \frac{\mathbb{1}}{4}$

$\varepsilon = 10^{-5}$

10^{20} molecule

n=2



Ensemble quantum computation.

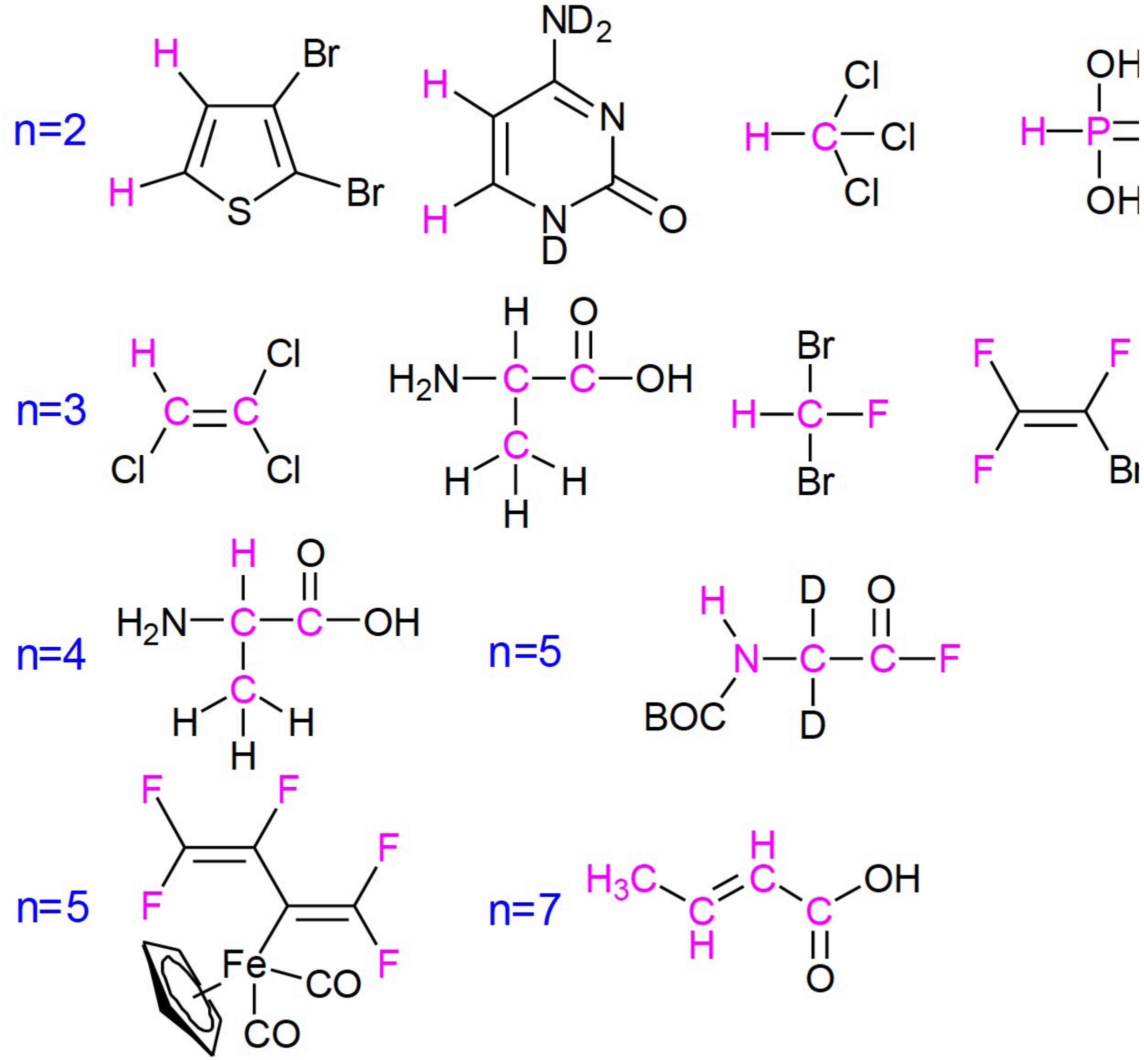
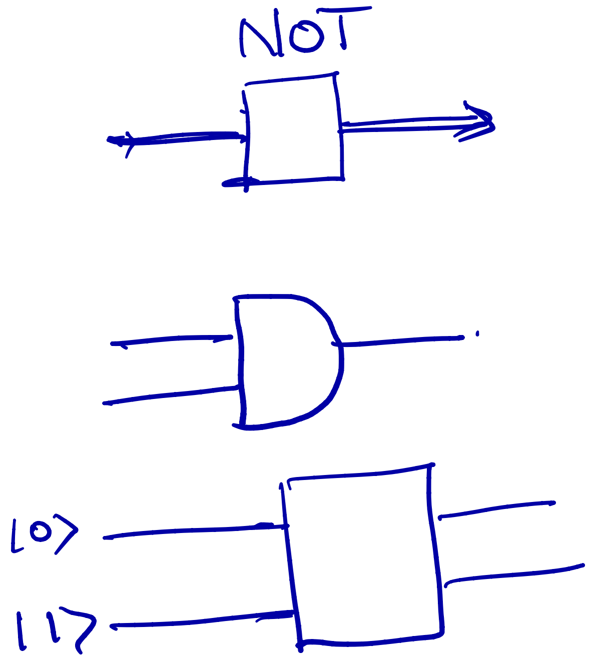
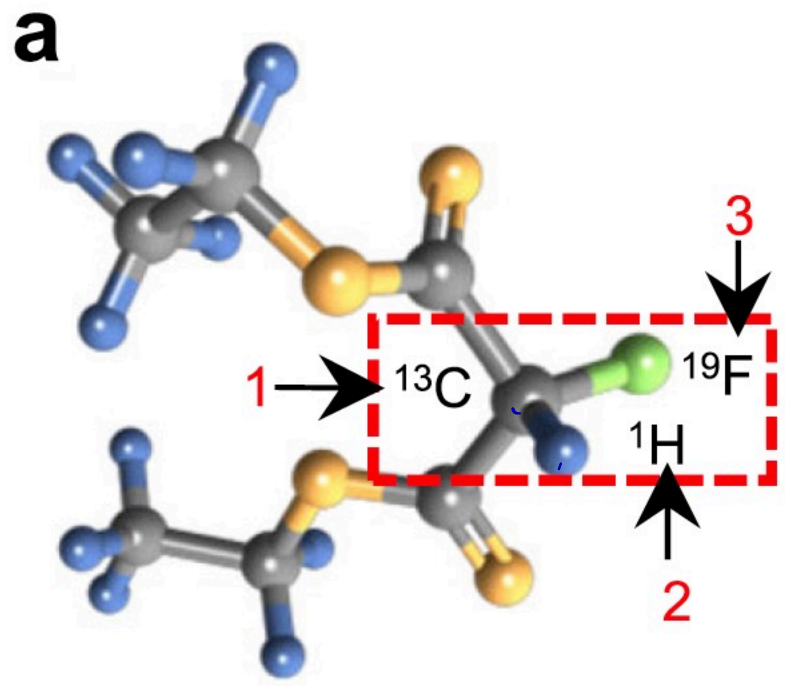


Fig. 6 A selection of molecules that have been used to implement quantum computing experiments. The number of qubits (n) is sho blue, while the nuclei used as qubits are indicated in pink. Note the seven qubit system the three ^{1}H nuclei in the methyl group ar as a single logical qubit.





Diethyl fluoromalonate

Chloroform.

Pro:

- Long decoherence times

  $T_1 \rightarrow$ Years

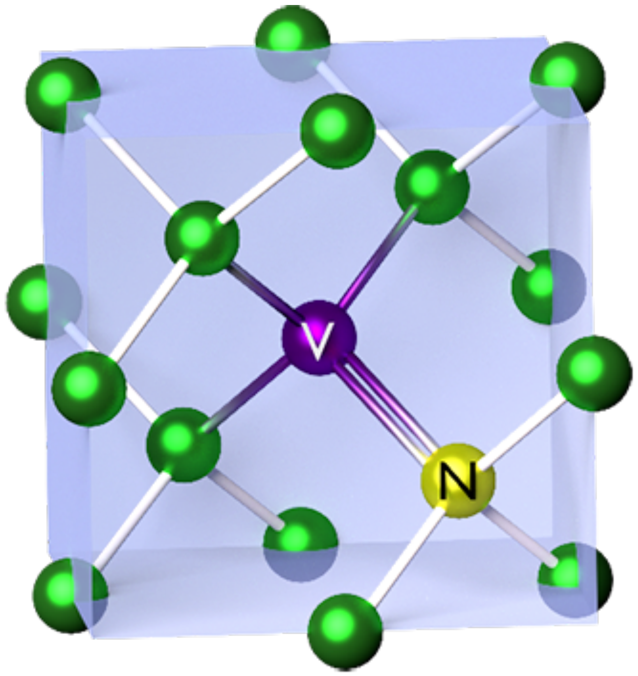
  $T_2 \rightarrow$ 10 Seconds

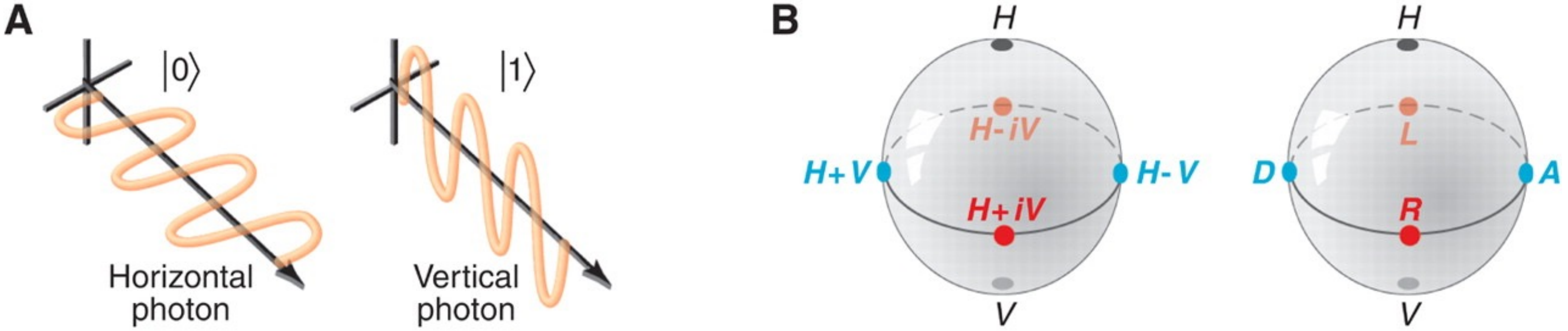
- Works at Room temperature

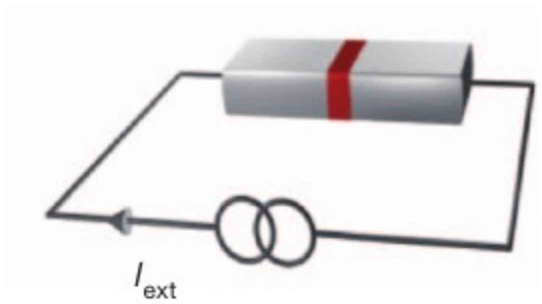
- Easy to implement multiqubit gate

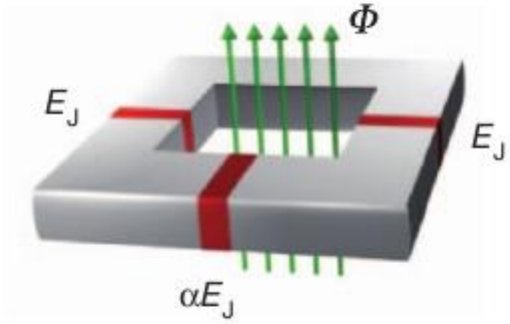
CON:

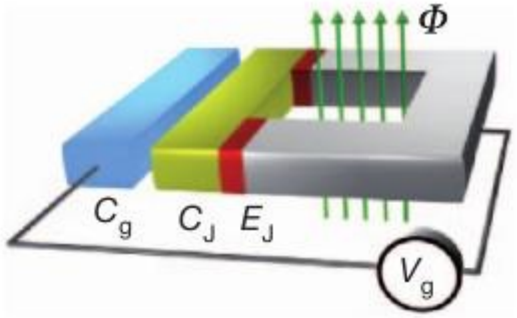
- Scalability
- Initialization
- Ensemble quantum computation

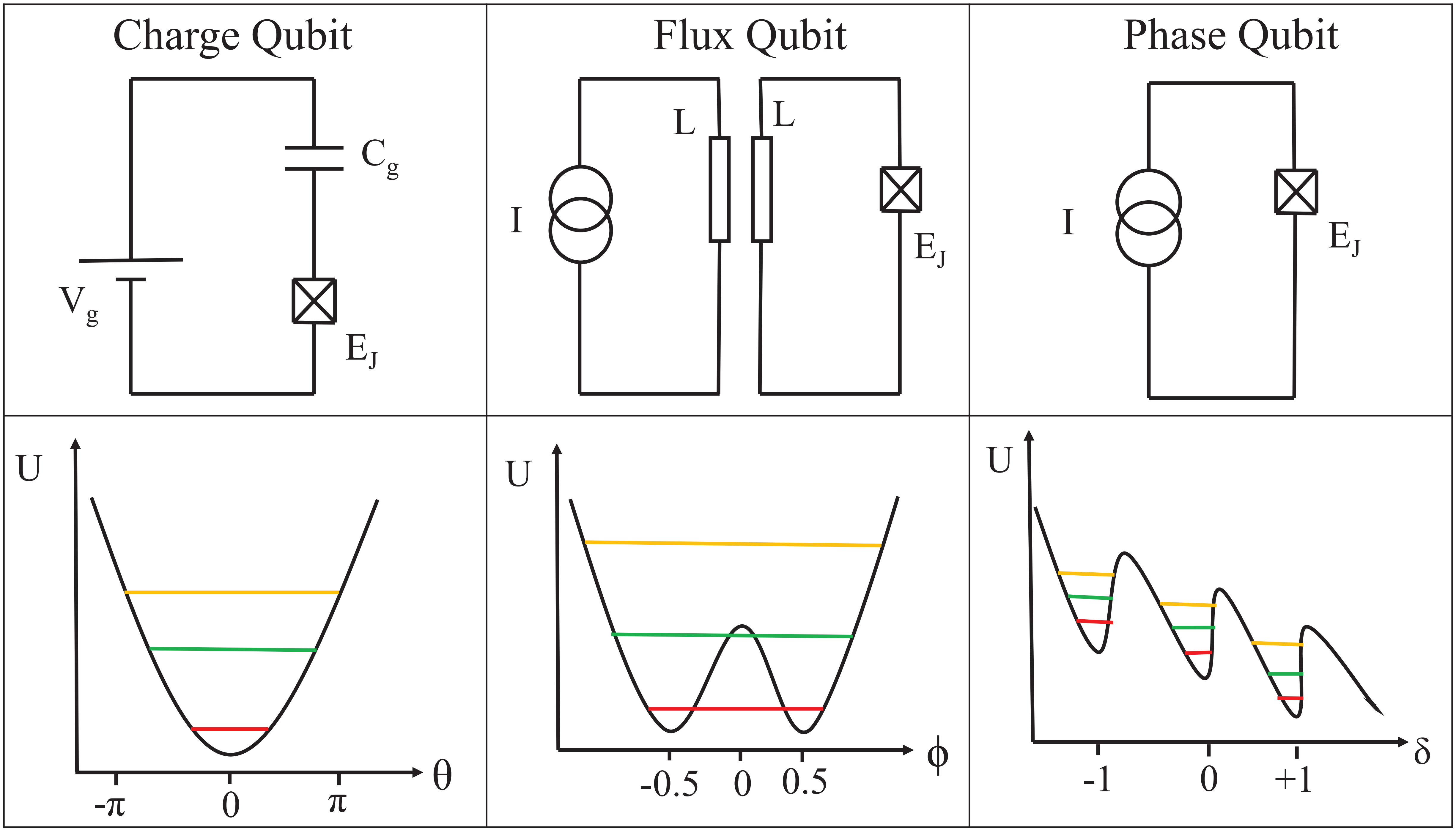

V
N


A
|0⟩
|1⟩
Horizontal photon
Vertical photon
B
H
H-iV
H+V
H-V
H+iV
V
H
L
D
A
R
V


I_{ext}


Φ
E_J
E_J
αE_J

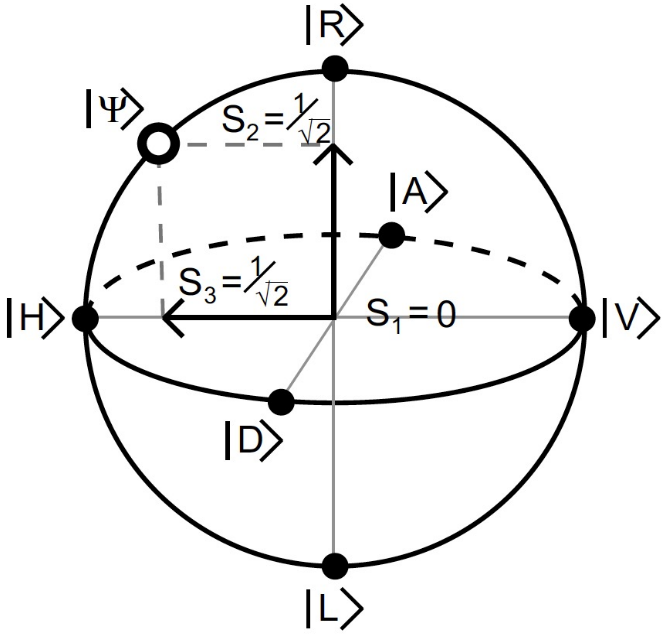

Φ
C_g
C_J
E_J
V_g



Charge Qubit
Flux Qubit
Phase Qubit
C_g
V_g
E_J
I
L
L
E_J
I
E_J
U
θ
-π
0
π
U
ϕ
-0.5
0
0.5
U
δ
-1
0
+1

Quantum State tomography for photonic states

Polarization as the levels of a qubit



Polarization states of a photon

Horizontal (H), Vertical (V)
Diagonal (D), Antidiagonal (A)
Right Circular (R), Left Circular (L)

Poincare sphere and Stokes parameter

$$\hat{\rho} = \frac{1}{2}\sum_{i=0}^{3} S_i \hat{\sigma}_i. \qquad S_i \equiv \mathrm{Tr}\left\{\hat{\sigma}_i \hat{\rho}\right\}$$

$$\begin{aligned} S_0 &= P_{|0\rangle} + P_{|1\rangle} \\ S_1 &= P_{\frac{1}{\sqrt{2}}(|0\rangle+|1\rangle)} - P_{\frac{1}{\sqrt{2}}(|0\rangle-|1\rangle)} \\ S_2 &= P_{\frac{1}{\sqrt{2}}(|0\rangle+i|1\rangle)} - P_{\frac{1}{\sqrt{2}}(|0\rangle-i|1\rangle)} \\ S_3 &= P_{|0\rangle} - P_{|1\rangle}, \end{aligned}$$

Qiskit

state_tomography_circuits, StateTomographyFitter
process_tomography_circuits, ProcessTomographyFitter

Reference:

1. http://research.physics.illinois.edu/QI/Photonics/tomography/
2. https://qiskit.org/documentation/tutorials/noise/8_tomography.html

Quantum Tomography

Tomography: Imaging by sections Ex: CT scan

Quantum Tomography: quantum state or process is reconstructed using measurements of an ensemble of identical quantum states.

Quantum Tomography

State Tomography

Process Tomography

Quantum state tomography: A quantum state is reconstructed using measurements on an ensemble of identical quantum states.
The measurements must be tomographically complete which means the operators must form a complete basis on the Hilbert space of the system.

Quantum process tomography: Quantum states are used to probe a quantum process.