SUPERCONDUCTING QUANTUM BITS

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CLASSICAL vs. QUANTUM INFORMATION

Classical equilibrium states

Quantum energy levels

\[ |\Psi\rangle = \alpha |0\rangle + \beta |1\rangle \]

Write: 0 OR 1
Read: 0 OR 1

Write: |0\rangle AND |1\rangle
Read: |0\rangle OR |1\rangle
CHOSING A QUANTUM TWO-LEVEL SYSTEM

Trapped Ions
(NIST)

Nuclear Magnetic Resonance
(IBM/MIT)

Superconducting Circuits
(SACLAY/YALE)

& Spins in Semiconductors, NV Centers in Diamond, e⁻¹ on LHe, Graphitic Circuits, Magnetic Molecules, etc

CAN ALL BE DESCRIBED (APPROXIMATELY) BY A TWO LEVEL HAMILTONIAN
QUANTUM INFORMATION SYSTEMS

- electrical access
- readily integrable
- engineered hamiltonian with "LEGO" blocks: capacitors, inductors and Josephson junctions

A.J. Leggett, 1982
HMMM... THE ENVIRONMENT!

Trapped Ions

- weak coupling to environment
- Long coherence times
- Weak qubit-qubit coupling (slow gates)

Superconducting Circuits

- strong coupling to environment
- Short coherence times
- Strong qubit-qubit coupling (fast gates)
SUPERCONDUCTING QUBITS

Electrical Circuit

“Artificial Atom”

Single Spin ½ NMR

|1> |0>
HOW CAN WE MAKE A CIRCUIT ATOM-LIKE?

Electrical Circuit

“Artificial Atom”
HOW CAN A SUPERCONDUCTING CIRCUIT BECOME QUANTUM-MECHANICAL AT THE LEVEL OF CURRENTS AND VOLTAGES?

SIMPLEST EXAMPLE: SUPERCONDUCTING LC OSCILLATOR CIRCUIT

MICROFABRICATION

\[ L \sim 3\text{nH}, \quad C \sim 10\text{pF}, \quad \omega_c/2\pi \sim 1\text{GHz} \]
LC OSCILLATOR AS A QUANTUM CIRCUIT

\[ [\phi, q] = i\hbar \]

\[ \phi = LI \]

\[ q = CV \]
LC OSCILLATOR AS A QUANTUM CIRCUIT

\[
[\phi, q] = i\hbar
\]

\[
\phi = LI
\]

\[
q = CV
\]

\[\hbar \omega_r > k_B T\]

1GHz 10mK
LC OSCILLATOR AS A QUANTUM CIRCUIT

\[ [\phi, q] = i\hbar \]

CANNOT STEER THE SYSTEM TO AN ARBITRARY STATE
THE JOSEPHSON TUNNEL JUNCTION: NON-LINEARITY AT ITS FINEST!

\[ I(\delta) = I_0 \sin(\delta) \]

(NON-LINEAR INDUCTOR)

\[ U(\delta) = -\frac{\hbar}{2e} I_0 \cos(\delta) \]
JOSEPHSON JUNCTION QUBITS

- **Phase Difference**
  - $\delta$

- **Current Qubit**
- **Charge Qubit**
- **Flux Qubit**

Mathematical expressions:
- $N_g = \frac{C_g U}{2e}$


\[ \hat{H} = \frac{E_{el}}{2} \hat{\sigma}_x - \frac{E_j}{2} \hat{\sigma}_z \]

\[ \hat{H}_{el} = 4E_c \left( \hat{n} - \frac{C_g U}{2e} \right)^2; \quad E_c = \frac{e^2}{2(C_g + C_j)} \]

\[ \hat{H}_j = -E_j \cos \hat{\theta}; \quad E_j = \varphi_0 i_0 \]
\[ \hat{H} = 4E_c (\hat{n} - N_g)^2 - 2E_j \cos\left(\frac{\Phi}{2\Phi_0}\right) \cos\hat{\theta} \]
READOUT STRATEGIES

**charge**

\[ Q_k \propto \frac{\partial E_k}{\partial N_g} \]

CPB + SET

**capacitance**

\[ C_k \propto \frac{\partial^2 E_k}{\partial N_g^2} \]

cQED Qubit

**current**

\[ I_k \propto \frac{\partial E_k}{\partial \Phi} \]

Quantronium

**inductance**

\[ L_k \propto \left( \frac{\partial^2 E_k}{\partial \Phi^2} \right)^{-1} \]

Quantronium + JBA

- work @ sweet spot
- readout @ sweet spot

Quantronium + JBA

- work @ sweet spot
- readout @ sweet spot

"sweet spot"
CAN’T READ CHARGE OR CURRENT!

\[
\begin{align*}
|0\rangle & \quad \left\{ \begin{array}{l}
Q_1 - Q_0 = 0 \\
C_1 - C_0 \neq 0
\end{array} \right.
\quad \text{charge noise}

|1\rangle & \quad \left\{ \begin{array}{l}
Q_1 - Q_0 \neq 0 \\
C_1 - C_0 = 0
\end{array} \right.
\quad \text{flux noise}
\end{align*}
\]

\[
\begin{align*}
I_1 - I_0 & \neq 0 \\
L_1 - L_0 & \cong 0
\end{align*}
\]

\[
\begin{align*}
I_1 - I_0 & = 0 \\
L_1 - L_0 & \neq 0
\end{align*}
\]
DISPERSIVE READOUT

- qubit state modifies oscillator frequency
- measure susceptibility, not loss
NON-LINEAR INDUCTIVE READOUT: QUANTRONIUM

Write

JJ=non-linear inductor

Read

Island
THE JOSEPHSON OSCILLATOR

\[ I(\delta) = I_0 \sin(\delta) \]
\[ V(t) = \frac{\hbar}{2e} \frac{d}{dt} (\delta) \]
\[ U(\delta) = -\frac{\hbar}{2e} I_0 \cos(\delta) \]

Nonlinear Oscillator

\[ L_J = \frac{V(t)}{\frac{dI}{dt}} = \frac{\hbar}{2e} \frac{1}{I_0} \frac{1}{\cos(\delta)} \]
\[ \omega_p = \frac{1}{\sqrt{L_J C}} \]
COMBINING HIGH SENSITIVITY & SPEED

LINEAR OSCILLATOR (review)

Q sets sensitivity

NON-LINEAR OSCILLATOR

kT sets sensitivity!
JOSEPHSON BIFURCATION AMPLIFIER

\[ i_{rf} \sin[\omega t + \phi(i_{rf}, I_0)] \]

\[ i_{rf} \sin[\omega t] \]

\[ \text{INPUT} \]

\[ I_0 \]

\[ \text{OUTPUT} \]

\[ 50\Omega \]

\[ \text{JBA: INPUT COUPLES TO } I_0 \]

- \( \phi(i_{rf}, I_0) \)
- \( P_{\text{switch}} (i_{rf}, I_0) \)
- minimal backaction
- no on-chip dissipation

\[ \omega = 0.9 \omega_p \]

\[ \phi \text{ (deg)} \]

\[ \phi < 0 \]

\[ I_0' < I_0 \]

\[ I_0 \]

\[ i_{rf} / I_0 \]
Essential Nonlinearities in Hearing

V. M. Eguiluz, M. Ospeck, Y. Choe, A. J. Hudspeth, and M. O. Magnasco

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THE CHALLENGE OF THE MICROWAVE EAR

\[ T = 10 \text{ mK} \]
\[ \nu = 1-20 \text{ GHz} \]
$T = 10 \text{ mK}$
$\nu = 1-20 \text{ GHz}$
SWITCHING DYNAMICS: TESTING THE “METER”

- histogram reflected phase $\phi$
  - record in 30ns
  - repeat at 4 MHz

- identify “meter” states

- hysteresis: sample & hold!
QUANTRONIUM with BIFURCATION READOUT

QUBIT CONTROL PULSE SEQUENCE (~ 20 GHz)

QUBIT STATE ENCODED IN REFL. PULSE PHASE $\phi$

READOUT PROBING PULSE (~ 1 GHz)
SPECTROSCOPIC FINGERPRINT

WEAKLY EXCITING PULSE, $\nu$

READOUT

$P_{\text{switch}}$

$\nu$ (GHz)

$\nu_{\text{sweet spot}} = 18.984 \text{ GHz}$
$\nu = \nu_{\text{sweet spot}}$

$\Delta \nu = -100 \text{MHz}$

$\Delta \nu = +100 \text{MHz}$
EXCITED STATE LIFETIME – $T_1$

Exponential decay, $T_1 = 1\text{--}5 \, \mu\text{s}$

$T_1 >> \text{readout time}$

Prepare qubit in $|1\rangle$ state

$|0\rangle$

$|1\rangle$

$\pi$

READOUT

$\text{t}_{\text{wait}}$

Graph showing exponential decay with $t_{\text{wait}}$ (μs) on the x-axis and $P_{\text{switch}}$ on the y-axis.
RABI OSCILLATIONS

32 million measurements
~ 10 min (dead time ~0.2 sec)
RAMSEY FRINGES

$T_2 = 300\text{ns}$

$P_{\text{switch}}$ vs $\Delta t (\text{ns})$
QUANTUM NON-DEMOLITION READOUT?

Measure once, vary time delay

\[ \pi \quad \rightarrow \quad t_{\text{wait}} (\mu s) \quad \rightarrow \quad \text{Time} \]

Measure multiple times

\[ \pi \quad \rightarrow \quad \text{Time} \]

- **Variable Delay**
- **Multi Pulse**

Graph showing the decay of \( P_{|1\rangle} \) over time with two different delay scenarios.
READOUT INDUCES LOSSES

VARY TEST PULSE

\[ \pi \]

READOUT PULSE

\[ \bar{p}_{|1\rangle} \]

GROUND STATE

\[ U_{rf} \]

\[ i_{rf} \]

\[ \bar{p}_{|1\rangle} \]

TIME (ns) 2000

EXCITED STATE

\[ U_{rf} \]

\[ i_{rf} \]

\[ \bar{p}_{|1\rangle} \]

T\_1 decay

TIME (ns) 2000

Readout loss
BALANCING ZEEMAN & STARK SHIFTS

\[ \Phi/\Phi_0 \]

\[ N_g \]

\[ V_{01} \text{ (GHz)} \]

\[ P_{\ket{1}} \]

\[ I_{\text{rf}} \text{ (nA)} \]

COMPENSATION PULSE

READOUT PULSE
CONCLUSIONS

SUPERCONDUCTING QUANTRONIUM QUBIT

$T_1 \sim 1-5 \mu s$, $T_2 \sim 0.5 \mu s$, $T_{\pi} \sim 1\text{ns}$

DISPERSSIVE MEASUREMENT: NO ENERGY LEFT BEHIND

FAST MEASUREMNT: MEASURE 30ns, RECORD 100ns

MINIMAL DEAD TIME: REPETITION RATE SET BY $T_1$

NON-INVASIVE: CAN TURN READOUT OFF

SINGLE SHOT: FIDELITY 67%
   VISIBILITY 87%

→ TAILOR MEASUREMENT TO MINIMIZE LOSSES