TOWARDS QUANTUM METROLOGY OF ELECTRICAL CURRENT IN JOSEPHSON CIRCUITS

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MOTIVATION: MESOSCOPIC EFFECTS OFFER THE “QUANTUM” DEFINITION OF MASS

ATOMIC CLOCK

AC Josephson effect

\[ V = n \frac{h}{2e} f \]

Single charge quantum effect

\[ f = \frac{I}{me} \]

NEEDS IMPROVEMENT!

Integer quantum Hall effect

\[ I = p \frac{e^2}{h} V \]
GENERAL PROBLEM: OFFSET CHARGE NOISE IN SINGLE-CHARGE DEVICES HINDERS APPLICATIONS

CHARGING AND OFFSET CHARGE NOISE

\[ E_C = \frac{1}{2} e^2 / C_J \quad E_J = \frac{1}{2} \Phi_0^2 / L_J \]

\[ H = 4E_C (\hat{N} - N_{\text{offset}})^2 - E_J \cos \hat{\phi} \]

\[ S_{N_{\text{offset}}} \sim 10^{-3} / \sqrt{\text{Hz}} \]

CHARGING AND OFFSET CHARGE NOISE

\[ E_J / E_C < 1 \]

No offset charges, but no charging either!

\[ E_J / E_C > 10 - 100 \]

Charging and offset charge noise

SET, CPB, Quantronium

SQUID, Transmon/Phase/Flux qubits
**Readout**

\[ f_0 = 8 \text{ GHz}; \quad Q=400 \]

**Small junction:**

\[ \frac{E_J}{E_C} = 3.6 \]

**Array (N=43):**

\[ \frac{E_{JA}}{E_{CA}} = 28 \]

*Main Idea*

Single Cooper-pair regime without charge noise, because every island is shunted by at least one large junction.
EC = \( \frac{1}{2} \frac{e^2}{(C_J + C_c)} = 2.5 \text{ GHz} \)

\[ E_J = \frac{1}{2} \left( \frac{\Phi_0}{2\pi} \right)^2 / L_J = 8.9 \text{GHz} \]

\[ E_L = \frac{1}{2} \left( \frac{\Phi_0}{2\pi} \right)^2 / L = 0.52 \text{GHz} \]

\[ \omega_R = \left( \frac{L_R C_R}{1} \right)^{1/2} / 2\pi = 8.2 \text{GHz} \]

\[ Z_R = \left( \frac{L_R}{C_R} \right)^{1/2} = 82 \Omega \]

**Coupling constant**

\[ g = \frac{\omega_R (Z_R / 2R_Q)^{1/2}}{(1 + C_J / C_c)} \]

\[ g = 135 \text{MHz} \quad (R_Q = 1 \Omega) \]

\[ C_J / C_c = 11 \]
LOCATING FLUXONIUM ON THE s-QUBIT MAP

\[ \Phi_{\text{ext}} = \frac{1}{2} \Phi_0 \]
\[ \Phi_{\text{ext}} = \frac{1}{4} \Phi_0 \]
\[ \Phi_{\text{ext}} = 0 \]

Potential energy

“hyperfine microwave atomic clock”

“quadrupole optical atomic clock”

\[ E_J / E_L \]

CPB  Quantronium  Transmon

Fluxonium

flux qubit

RF-SQUID, phase qubit

\[ \approx 2E_J \]

\[ 2\pi \]

\[ 2\pi \]

\[ 4\pi \]
READOUT: MEASURE ATOM SUCCEPBTIBILITY VIA RESONANT REFLECTION OFF THE CAVITY

- Periodic response to magnetic flux – the 44 junction loop is superconducting!
- Strong interaction of multiple atomic transitions with the readout resonator

Measure complex reflection amplitude @ 8.175 GHz
2-TONE SPECTROSCOPY NEAR $\Phi_{\text{ext}} = 0$

Inset: 0→2 transition symmetry-forbidden at zero flux

0→3 transition

Parasitic resonance in the array (accounted by a minor model correction)
2-TONE SPECTROSCOPY NEAR $\Phi_{\text{ext}} = \Phi_0 / 2$

Need 2 digits to label combined atom+cavity transitions:
First: Atomic level number
Second: Cavity photon number
SINGLE COOPER PAIR REGIME
WITHOUT CHARGE OFFSETS
NEW CIRCUIT ELEMENT: “SUPERINDUCTANCE” *

- Perfect “Short” @DC
  \rightarrow No offset charge noise

- Reactance \geq \hbar/(2e)^2 @RF
  \rightarrow Protects large (> \pi) phase fluctuations across the small junction

* Term by A. Kitaev
NOVEL PURCELL EFFECT FREE READOUT: FIDELITY UNCOMPROMISED BY STATE COHERENCE

\[ g_{12} = g <1|N|2> \approx 100\text{MHz} \]
\[ \omega_{12} - \omega_R \approx 1\text{GHz} \]
\[ \chi = \frac{g_{12}^2}{(\omega_{12} - \omega_R)} \approx 10\text{MHz} \]
At the same time \( \omega_{01} \ll \omega_R \)

atom transition 0-1 to store/manipulate
atom transition 1-2 to couple to readout
TIME - DOMAIN COHERENT STATE CONTROL

$T_{\text{Rabi}} \sim 1 \text{ us, cooling/heating independent!}$

Pulse protocol

sideband

qubit varies
cavity
time
TIME-DOMAIN REVERSIBLE TUNNELING OF FLUXONS

**Eigenstates**

- $|0\rangle$
- $|1\rangle$

$-\hbar/4e$  $+\hbar/4e$

**“Pointer” States**

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

$-\hbar/4e$  $+\hbar/4e$

**Pi/2 Pulse**

- $|0\rangle \rightarrow |0\rangle + |1\rangle$
- $|0\rangle + |1\rangle \rightarrow |0\rangle - |1\rangle$
- $|0\rangle + \pm |1\rangle \rightarrow \begin{cases} |1\rangle & \text{Pi/2 pulse} \\ |0\rangle & \text{read} \end{cases}$

**Ramsey Interference**

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

**Dynamical Parameters**

- $\Delta = 369$ MHz
- $T_2 = 250$ ns

**Graphs**

- Reflected phase, deg vs. Free evolution time, ns
- Frequency spectrum

TOWARDS BLOCH OSCILLATIONS...

Now exists!

Effective single JJ

JJ array

Linear/non-linear microwave readout (the JBA)

\[ \Delta f = \frac{I}{2e} \]
CONCLUSIONS

CHARGING REGIME WITHOUT CHARGE OFFSETS LEADS TO A NOVEL ARTIFICIAL ATOM WITH USEFUL “Λ” SPECTRUM AND REDUCED JUNCTION AND BIAS PARAMETER DEPENDENCE

JOSEPHSON ARRAY ACTS AS AN INDUCTOR WITH
> 20 kΩ REACTANCE AND < 1 Ω RESISTANCE @ 10GHz

PERSPECTIVES

FAST READOUT OF PURCELL-FREE TRANSITIONS TO DEMONSTRATE “SHELVING” OF QUANTUM INFORMATION IN SOLID STATE CIRCUITS

ORIGINS OF RELAXATION AND DEPHASING IN JOSEPHSON CIRCUITS

METROLOGY WITH BLOCH OSCILLATIONS BY CURRENT BIASING OF A SMALL JUNCTION VIA SUPERINDUCTIVE LEADS