Metastable states in an RF driven Josephson oscillator

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Acknowledgements: M. Dykman
INTRODUCTION

DOUBLY CLAMPED MECHANICAL RESONATORS

MICROMECHANICAL TORSIONAL OSCILLATOR

<table>
<thead>
<tr>
<th>RESONANT FREQ.</th>
<th>~ 90 MHz</th>
<th>~3 KHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>QUALITY FACTOR</td>
<td>~7000</td>
<td>~2000 - 8000</td>
</tr>
<tr>
<td>TEMPERATURE</td>
<td>4K</td>
<td>4K - 77K</td>
</tr>
<tr>
<td>TRANSITIONS</td>
<td>ADDED NOISE</td>
<td>ADDED NOISE</td>
</tr>
</tbody>
</table>
INTRODUCTION

ELECTRICAL OSCILLATOR

RESONANT FREQUENCY ~ 1.5 GHz
QUALITY FACTOR ~ 20

TEMPERATURE: 10 - 200 mK

CLASSICAL TO QUANTUM DYNAMICS

FAST DYNAMICS ~ nanoseconds
OUTLINE

**Josephson Junction**
- Non-dissipative, non-linear circuit element

**RF biased Josephson Junction**
- Driven, non-linear oscillator
- Metastable states; transitions
- Quantum regime

**Applications**
Josephson relations

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

\[ I_0 \quad \text{critical current} \]

\[ V = \frac{\hbar}{2e} \frac{d\delta}{dt} = \phi_0 \frac{d\delta}{dt} \]
DC CURRENT BIAS

\[ I_{DC} < I_0 : \langle V \rangle = 0 \]

\[ I_{DC} > I_0 : \langle V \rangle \neq 0 \]

SUPERCONDUCTING

DISSIPATIVE
RF DRIVEN NON-LINEAR OSCILLATOR

\[ \phi_0^2 C_J \frac{d^2 \delta}{dt^2} + \frac{\phi_0^2}{R} \frac{d \delta}{dt} + \phi_0 I_0 \sin \delta = \phi_0 I_{RF} \sin \omega t \]

DRIVEN STATES IN THE SAME WELL

NO TRANSITIONS OUT OF THE WELL
TWO DYNAMICAL STATES

\[ \delta(t) = \delta_{\text{max}} \sin(\omega t + \gamma) \]

\[ \omega_p = \sqrt{\frac{I_0}{\varphi_0 C_J}} \]

\[ Q = \omega_p RC_J \]

If \[ \omega_p - \omega > \frac{\omega_p \sqrt{3}}{2Q} \] \[ \rightarrow \text{bistability} \]

Dynamical states differ in oscillation amplitude & phase
THE REFLECTION EXPERIMENT

OSCILLATOR

ENVIRONMENT

50 OHM CHARACTERISTIC IMPEDANCE
MINIMIZING NOISE

USE CIRCULATOR TO PROTECT SAMPLE FROM IN-BAND NOISE
MINIMIZING NOISE

USE FILTERS TO PROTECT SAMPLE FROM OUT OF BAND NOISE
JUNCTION + MICROWAVE CAPACITOR

Si₃N₄

Cu

30 pF
1 mm

εᵣ = 7.5

Al/Al₂O₃/Al
Junction (1 µA, 0.330 nH)

METALLIC UNDERLAYER
NON-LINEAR RESONANCE

\[ k_{B}T/E_{J} \]

\[ Q = \frac{1}{\omega p RC} \]

HYSTERESIS AND BISTABILITY

EXPLOIT HYSTERESIS TO IMPROVE SIGNAL TO NOISE RATIO

TRANSITION RATES

\[ \Gamma = \frac{\omega}{2\pi} \exp \left( -\frac{\Delta U}{k_B T} \right) \quad (kT \gg \hbar \omega) \]

\[ \Delta U^{\text{dyn}} = U_0 \left( 1 - \left( \frac{I_{\text{RF}}}{I_B} \right)^2 \right)^{3/2} \]

MEASURING ESCAPE TEMPERATURE

\[ \beta^{2/3} = \left[ \frac{U_0}{k_B T_{\text{esc}}} \right]^{2/3} \left( 1 - \frac{I_{RF}^2}{I_B^2} \right) \]

Exponential decay of population

Escape rate vs drive amplitude
MEASURING ESCAPE TEMPERATURE

$\beta^{2/3}$

$I_{RF}^2 / I_B^2$

200 mK

12 mK
Good agreement with quantum activation theory

Need higher oscillator frequencies

Marthaler et. al. arXiv:cond-mat/0602288
JOSEPHSON BIFURCATION AMPLIFIER

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

\[ \phi (i_{rf}, I_0) \]

\[ P_{\text{switch}} (i_{rf}, I_0) \]
QUBIT READOUT

QUBIT CONTROL
PULSE SEQUENCE
(~ 20 GHz)

QUBIT STATE
ENCODED IN REFLECTED
PULSE PHASE $\phi$

READOUT PROBING
PULSE (~ 1 GHz)
NON-LINEAR CAVITY RESONATORS

Superconducting Nb 1D cavity (1-10GHz)
Al-AlO-Al junction ($I_0 \sim 0.5-5 \mu A$)

See the following talks later today for more details:

W39.0002 (Vladimir Manucharyan, 2.42 pm, Room 342)
W39.0003 (Etienne Boaknin, 2.54 pm, Room 342)
W39.0004 (Michael Metcalfe, 5.06 pm, Room 342)
CONCLUSIONS

WELL CONTROLLED NON-LINEAR OSCILLATOR AT GHz FREQUENCIES

INTERESTING ESCAPE PHYSICS IN THE QUANTUM REGIME

HIGH FIDELITY QUBIT READOUT

TOOLBOX FOR SENSITIVE DETECTORS AND AMPLIFIERS
SLIDES AFTER THIS ARE ADDITIONAL
DC CURRENT BIAS II: Metastability & Switching

\[ \Gamma_{0 \to 1} (I_0, I_{DC}, T) = \frac{\omega_p}{2\pi} \exp \left( -\frac{\Delta U}{kT} \right) \]

\[ \Delta U (I_0, I_{DC}) = \left[ \frac{2\sqrt{2}}{3} \frac{\hbar}{e} I_0 \right] \cdot \left( 1 - \frac{I_{DC}}{I_0} \right)^{3/2} \]

\[ \left[ \ln \left( \frac{\omega_p}{2\pi \Gamma(I_{DC})} \right) \right]^{2/3} = \left[ \frac{2\sqrt{2}}{3} \frac{\hbar}{e k_B T} \right]^{2/3} \left( 1 - \frac{I_{DC}}{I_0} \right) \]

Extract \( I_0 \) and escape temperature \( T_{esc} \)
DC CURRENT BIAS III: Macroscopic Quantum Tunneling (MQT)

Martinis et al., PRB 35 (1987)

\[ I_0 = 1.14 \mu A \]

\[ T^* = 5 \text{mK} \]

\[ T > T^* = \frac{\hbar \omega_p}{7.2k} : \Gamma \propto e^{\frac{-\Delta U}{kT}} \]

\[ T < T^* = \frac{\hbar \omega_p}{7.2k} : \Gamma = \text{constant} \]
“SOFTENING” POTENTIAL

- Frequency decreases with drive amplitude

- For $\omega < \omega_p$, weak drive $\rightarrow$ off resonance
  strong drive $\rightarrow$ on resonance
\[ \delta(t) = \delta_{\parallel} \sin(\omega t) + \delta_{\perp} \cos(\omega t) \]
PHASE DIAGRAM: EXP & THY IN GOOD AGREEMENT

All parameters in prediction measured experimentally!
