COHERENT QUANTUM PHASE SLIP
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Coherent Quantum Phase Slip:

Exact quantum dual to Josephson Tunneling
(Coulomb blockade is a “partial” dual)

Degree of freedom in superconductor: Phase and Charge

Nature doi: 10.1038/nature 10930, 2012

**Exact duality**

**Josephson Current:** \( I_c \sin \phi \)

**Kinetic Inductance:** \( \Phi_0 (2\pi I_c \cos \phi)^{-1} \)

**Shapiro Step:** \( \Delta V = n \Phi_0 \nu \)

**CQPS Voltage:** \( V_c \sin(2\pi q) \)

**Kinetic Capacitance:** \( 2e (2\pi V_c \cos(2\pi q))^{-1} \)

**Shapiro Step:** \( \Delta I = n 2e \nu \)

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

\( \phi = \text{Phase across junction} \)

\( q = \text{Cooper-pair transferred (continuous number)} \)
Duality to the Josephson Effect

Josephson junction

Quantum phase-slip junction

\[ E_J = E_{J0} \cos \varphi \]

\[ E_{CQPS} = E_0 \cos \chi \]

\[ \frac{1}{L_J} = \left( \frac{2\pi}{\Phi_0} \right)^2 \frac{\partial^2 E_J}{\partial \varphi^2} \sim E_{J0} \]

\[ \frac{1}{C_k} = \left( \frac{2\pi}{2e} \right)^2 \frac{\partial^2 E_{CQPS}}{\partial \chi^2} \sim E_0 \]

Z ↔ Y  
L ↔ C  
\( \Phi_0 \leftrightarrow 2e \)

The CQPS is completely dual to the Josephson effect
Phase-slip in superconducting nanowires

Thermal phase slip:

Finite voltage across superconducting wires

Complex GL wavefunction $\psi$ in 1-D

Phase Rotation with Current

Uniform Solution

Nonuniform Solution $\Rightarrow$ Phase Slip

Tinkham
Phase-slip in superconducting nanowires

Coherent Quantum Phase-Slip

CQPS Qubit:

J. E. Mooij, C. J. P. M. Harmans,

\[ \Gamma_{cqp} = \alpha \exp \left( -\beta \frac{R_n}{R_c} \right) \]

\[ \Delta = \eta \Gamma_{cqp} \]

 Exact dual
 Charge Qubit

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Superconducting qubits

- Quantized charge: $2e: |N\rangle, |N+1\rangle$
- Quantized flux: $\Phi_0: |\downarrow\rangle, |\uparrow\rangle$

Charging energy: $E_c = 4e^2/C$
Josephson (tunneling) energy: $E_J$
Magnetic energy: $E_L = \Phi_0^2/L$
Phase-slip energy: $E_S$

Necessary condition: $E_{\text{qubit}} \gg kT$

- Charge qubit: $E_c \gg E_J$
- Flux qubits: $E_J \gg E_c$
- Phase-slip qubit: $E_L \gg E_S$
Device characteristics

**CQPS: superconducting wire**

\[ E_{cqp} \propto \alpha \exp\left(-\beta \frac{R_Q A}{\rho \xi}\right) \]

**Inductive energy**

\[ E_k = \frac{\Phi_0^2}{L} \]

\[ L_{\square} = 0.14 \frac{\hbar R_{\square}}{k_B T} \]

\[ E_k \gg E_{cqp} > k_B T \]

**Josephson energy**

\[ E_J \propto \alpha' \exp\left(-\beta' t \sqrt{\phi}\right) \]

**CQPS energy**

**Josephson : insulator**

**InO_x film**

- \( t = 35 \text{ nm} \)
- \( T_c = 2.7 \text{K} \)
- \( R_{\square} = 1.7 \text{k}\Omega \)

**Disordered superconductor for large \( \rho \)**

- \( \xi: \) coherence length
- \( \rho: \) resistivity (<\( T_c \)
Superconductivity Phase Diagram

Temperature

Magnetic Field

H_c

T_c

R_Q

INSULATOR

SUPERCONDUCTIVE

METAL

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Device configuration
CQPS flux qubit + resonator

Energy levels

\[ E = N\Phi_0, \quad (N+1)\Phi_0, \quad (N+1/2)\Phi_0, \quad \Phi_{ext} \]

Phase Slip Qubit (like flux qubit)
InO film
\[ R \sim R_0 \]

Gold gound-planes

InO\(_x\)

Coplanar lines

0.5 mm

40 nm

5 \(\mu\)m

10 \(\mu\)m
Transmission at the resonator resonance under qubit excitation

Transmission phase modulation

Resonance with the qubit ground state and excited state
Two-level spectroscopy

The dashed line is a fit to the energy splitting with $E_s/h = 4.9$ GHz, $I_p = 24$ nA.
Spectroscopy of the system in a wide ranges

\[
\Delta E/h = \frac{\sqrt{(2I_p \Phi)^2 + E_s^2}}{h}
\]

- Direct (single-photon) excitation, \(\Delta E/h = f_{\text{probe}}\) (blue dots)
- Two-photon process, \(\Delta E/h = f_{\text{probe}} + f_4\) (green dots)
- Three-photon process \(\Delta E/h = 2f_{\text{probe}} + f_4\) (red dots)
- \(f_{\text{probe}} \leq 35\) GHz,
- The dashed line: calculated with \(E_s = 4.9\) GHz and \(I_p = 24\) nA
**CQPS in other materials**

Requirements: $R_\square > 1 \, \text{k}\Omega$, suppressed Tc

- ALD grown TiN films, $R_\square \approx 3 \, \text{k}\Omega$ (*TU Delft, Klapwijk’s group*)
- Spattered NbN films, $R_\square \approx 2 \, \text{k}\Omega$ (*MSPU, Goltsman’s group*)

Nano-wire ~ 35 nm
**NbN film qubits**

20 qubits in a resonator

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**Transmission**

**Spectroscopy**
TiN qubits

In MW measurements $T_c \approx 0.8$ K
$L \approx 1.6$ nH/sq

Transmission through 1.5 mm Length coplanar resonator

Spectroscopy
NbN qubits: Dynamics

Quantum oscillations
Switching time \( t \gg RC \sim \text{ps} \)

**Josephson Electronics**
- flux quanta (phase)
- current
- parallel element
- inductive coupling

**Single Electronics**
- charge (number)
- voltage bias
- serial element
- capacitive coupling

**Exact duality**

**Advantage!**
Switching time
\[ t \sim L/R \sim \text{ps} \]

- DC SQUID
- RF SQUID
- Josephson memory
- SFQ device
- Resistively Couple Device

- Single Elect. Transistor
- Single Elect. Box
- Single Elect. Trap
- Single Elect. Turnstile
- Resistively Coupled SET
**QUANTUM CURRENT STANDARD:** Electron Pump $I = \epsilon f$

**Quantum Phase Slip**

![Quantum Phase Slip Image]

O. V. Astafiev et al., Nature 484, 355 (2012)

**Single electron transistor**

![Single electron transistor Image]

Keller et al., APL 69, 1804 (1996)

**Cooper pair sluice**

![Cooper pair sluice Image]

Niskanen et al., PRL 91 177003 (2003)

**Surface acoustic wave**

![Surface acoustic wave Image]

J. Ebbecke et al., APL 84, 4319 (2004)

**Optically driven electron pump**

![Optically driven electron pump Image]


**Nanomechanical single-electron shuttle**

![Nanomechanical single-electron shuttle Image]


**Tunable Barrier Pumping**

![Tunable Barrier Pumping Image]


**Nonlocal electron hole turnstile**

![Nonlocal electron hole turnstile Image]

F. Battista and Samuelsson, PRB 125324 (2011)

10 – 100pA with $10^{-7}$
Voltage: **Josephson Effect** (Nobel 1973)

Resistance: **Quantized Hall Effect** (Nobel 1985)

Voltage: $V = \frac{h \nu}{2e}$

Resistance: $R = \frac{h}{e^2}$

Current:
- Coherent quantum phase slip
- SINIS pump
- Semiconductor pump
- SET pump, Turnstile

Accuracy: $< 3 \times 10^{-19}$

COMPETITION

Topological Protection!
Topological Protection

Phase rotation

Macroscopic Phase $\phi$

$$\frac{d\phi}{dt} = \frac{V}{\Phi_0}$$

Cyclotron orbits

Electron Orbit

$$\mathbf{v}_E \times \mathbf{B}$$

Landau level

$$E_n = \hbar \omega_c (n + 1/2)$$

$$\omega_c = \frac{eB}{m}$$

Quantized Hall

$G_{Hall}$

Phase lock w/ External Microwave

$$V$$

I

$\frac{h\nu}{2e}$

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A Brief History of Superconductivity

1911: Supercurrent, (Nobel 1913)

1933: Meissner Effect


1957: BCS Theory, (Nobel 1972)

1962: Josephson Effect, (Nobel 1973)

1999: Macroscopic Quantum Coherence, (Josephson qubit)

2012: Coherent Quantum Phase Slip (CQPS)
Conclusion

- Coherent Quantum Phase Slip has been experimentally demonstrated
- Phase-slip qubit has been realized in thin highly disordered films of InO$_x$, NbN and TiN
- DC characterization is underway
Thank you for your attention and Congratulations Aono-san!