Strong tunable coupling between a charge and a phase qubit

Wiebke Guichard
Olivier Buisson
Frank Hekking
Laurent Lévy
Bernard Pannetier

Aurélien Fay
Ioan Pop
Florent Lecocq
Rapaël Léone
Nicolas Didier
Julien Claudon
Franck Balestro

CNRS – Université Joseph Fourier
Institut Néel- LP2MC
GRENOBLE

Zhihui Peng
Emile Hoskinson
Alex Zazunov

Scientific collaborations:
PTB Braunschweig (Germany)- EuroSQIP project
LTL Helsinki (Finland)
KTH Stockholm (Sweden)
Rutgers (USA)
Introduction

In the last decade:
- new experiences in quantum mechanics using superconducting quantum circuits

- realisation of a two level system (Saclay)
- anharmonic quantum oscillator (multi-level system) (Grenoble)
- two level system coupled to high Q cavity (Yale, Zurich, Boulder)

- two coupled qubits (Control-NOT, i-SWAP, …) (NEC, Delft, Santa Barbara)

Motivations:
- quantum dynamics in macroscopic system
- new quantum phenomena
  * very strong coupling with external field
  * strong coupling with environment
- model system for the quantum nano-electronics
Outline

- Introduction to superconducting quantum circuits
- Description of the circuit
- dc-SQUID: phase qubit
- Asymmetric transistor: charge qubit
- Tunable coupling between the charge and phase qubit
- Summary
Introduction of the superconducting state

In many metals, $T$ smaller than a critical temperature:
The conduction electrons condense to electron pairs: Cooper pairs

\[ e \quad \Delta \quad 2e \]

All the pairs forms a Macroscopic Quantum State: \( |\Psi_G> \)

\[ |\Psi_G> \text{ is analog to the coherent state of a laser beam} \]

\[ \text{the phase is very well defined} \]

\[ |\Psi_G> \text{ is a very stable ground state} \]

\[ \text{because no excitations below the gap} \]

Persistent current without any decay!

To perform complex quantum experiments, we need excited levels

Josephson junction
The Josephson energy (I)

Coupling between two superconductors: a tunnel barrier

![Diagram showing two superconductors connected by a tunnel barrier](image)

Josephson equations:

\[
\begin{align*}
I &= I_c \sin(\varphi_1 - \varphi_2) \\
V &= \frac{\Phi_0}{2\pi} \frac{d(\varphi_1 - \varphi_2)}{dt}
\end{align*}
\]

where

\[
I_c = \frac{\pi \Delta}{2eR_n}
\]

and

\[
\Phi_0 = \frac{\hbar}{2e} = 2.07 \times 10^{-15} \text{T.m}^2
\]

The Josephson energy:

\[
E_J = \frac{\Phi_0 I_c}{4\pi}
\]

Energy:

\[
E_J = -E_J \cos(\varphi_1 - \varphi_2)
\]
The Josephson energy (II)

Josephson inductance:

Josephson equations:

\[
\begin{align*}
I &= I_c \sin(\varphi) \\
V &= \frac{\Phi_0}{2\pi} \frac{d\varphi}{dt}
\end{align*}
\]

Linear limit: \(\sin(\varphi) \approx \varphi\)

Josephson junction \leftrightarrow Inductance: \(L_J = \frac{\Phi_0}{2\pi I_c}\)

Because of « sin » current-phase relation:

Non-linear inductance:

\[
L_J(I) = \frac{\Phi_0}{2\pi I_c} \frac{1}{(1 - (I / I_c)^2 / 3)}
\]

SQUID:

Josephson energy: flux dependent

\[
\Phi \quad E_J(\Phi_b) = \frac{\Phi_0 I_c}{2\pi} \left| \cos(\pi \Phi_b / \Phi_0) \right|
\]
The charging energy

Capacitance effect:

\[ 2e \]

\[ Q = -2e \quad Q = +2e \]

The charging energy:

\[ E_c = \frac{(2e)^2}{2C} \]

\[ \text{Energy} = E_c \hat{n}^2 \]
The Josephson junction dynamics

\[ H = E_C \hat{n}^2 - E_J \cos(\hat{\phi}) - \frac{\Phi_0 I_b}{2\pi} \hat{\phi} \]

Conjugate variables: \( [\hat{n}, \hat{\phi}] = i \)

\( E_c \gg E_J \)
\( \Delta \phi \gg 1 \)
\( \Delta Q \ll 1 \)
Coulomb blockade

\( E_c \ll E_J \)
\( \Delta \phi \ll 1 \)
\( \Delta Q \gg 1 \)
Supra
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- **Description of the circuit**
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Hybrid superconducting two-qubits system

Asymmetric Cooper pair transistor (ACPT)
Superconducting island ~ 0.12 µm²

Charge qubit

dc-SQUID: superconducting loop interrupted by 2 Josephson junctions

Phase qubit

3-angle shadow evaporation
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dc-SQUID: phase qubit

\[ H = E_C \hat{n}^2 - E_J \cos(\hat{\Phi}) - \frac{\Phi_0 I_b}{2\pi} \hat{\Phi} \]

A quantum anharmonic oscillator

\[ H_s = \frac{1}{2} \hbar \omega_p \left[ \hat{P}^2 + \hat{X}^2 \right] - \hbar \sigma \hat{\omega}_p \hat{X}^3 \]

Excitation \hspace{1cm} Microwave flux: \( \Phi(t) \)

\( \Phi = 0.02 \Phi_0 \)

\( \Delta \nu = 13 \text{MHz} \)
Quantum measurements

A nano-second flux pulse reduces the barrier

Hysteretic junction: escape leads to voltage

\( V = \left( \frac{\Phi_0}{2\pi} \right) \gamma \)
Phase qubit spectroscopy

\( \Phi_S = 0.02 \Phi_0 \) \hspace{1cm} I_{\text{bias}} = 1890 \text{ nA}
Coherent oscillations in a dc SQUID


- Anharmonic oscillator:
  \[ \nu_{01} \]

Anharmonicity: \( \nu_{01} - \nu_{12} = 160 \text{ MHz} \)

- Flux-pulse sequence:
  \[ \nu_{\text{MW}} = \nu_{01} \]
  \[ T_{\text{MW}}: \text{ tunable} \]

Rabi like oscillations!

\[ \nu_{MW} = \nu_{01} \]

\[ T_{\text{MW}}: \text{ tunable} \]
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**Charge qubit spectroscopy**

Asymmetric Cooper pair transistor

\[ n_g = C_g V_g / 2e \]

\[ \delta(\Phi_T, \Phi_S, I_b) \]

\[ \hat{H}_T = \frac{(2e)^2 (\hat{n} - n_g)^2}{2C_\Sigma} - \sum e_j \cos(\delta/2) \cos(\Theta_d) \]

\[ - \Delta e_j \sin(\delta/2) \sin(\Theta_d) \]

A charge qubit:

\[ \hbar \nu_t(\delta, n_g) \]

\[ P_{esc} \]

\( \nu_T = 8.779 \text{ GHz} \)
Charge qubit frequency versus $n_g$

$$E_C = \frac{(2e)^2}{2C_\Sigma} \sim 26.7 \text{ GHz}$$
Charge qubit frequency versus $\delta$

Josephson asymmetry

$$\mu = \frac{E_{j1} - E_{j2}}{E_{j1} + E_{j2}} = 41.9\%$$

$$E_{j}/E_C \approx 0.8$$

optimal point
($\delta = 0$, $n_g = 0.5$)

$E_{j1} + E_{j2} \approx 21.8$ GHz

Quantronium Saclay

optimal point
($\delta = \pi$, $n_g = 0.5$)

$E_{j2} - E_{j1} \approx 8.8$ GHz
Rabi oscillations (charge qubit)

\[ |+\rangle \uparrow \nu_{\mu w} = \nu_T \downarrow |-\rangle \]

\[ \nu_{Rabi} \approx 20.4 \text{ MHz} \]

\[ T_2^{\text{Rabi}} \approx 110 \text{ ns} \]

\[ A_{\mu w} \]

\[ V_g \]

\[ \text{\mu wave duration} \]
Relaxation (charge qubit)

\[ P_{\text{ech}} \propto e^{-\frac{t}{T_1}} \]

\( T_1 \sim 0.8 \mu s \)
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Coupling between the two qubits

\[ \hat{n}_T(I_b, \Phi, V_g) \]

\[ \hat{n}_0(I_b, \Phi) \]
Coupled qubits spectroscopy

Spectroscopy at $I_{\text{bias}} = 1890$ nA

$n_g = 1/2$

Phase qubit $|-, 1\rangle$

Charge qubit $|+\rangle, |0\rangle$

Frequency (GHz)

$\Phi_0 / \Phi$
Spectroscopy versus $n_g$

- **Resonant coupling at $n_g = 0.5$**

- $\nu_T$ for ACPT

- $\nu_S$ for dc-SQUID

- $\nu = 18.98 \text{ GHz}$

- $\alpha \approx 110 \text{ MHz}$

- $\nu_S$ does not depend on $n_g$
Spectroscopy versus flux

- Two qubits can be in resonance from 9 GHz to 20 GHz.
- Strong variation of the coupling strength.
Resonant coupling

Coupling varies from 60 MHz to 1100 MHz, factor of 18
Electrical schematic of the circuit

\[ \hat{H} = \hat{H}_{ACPT} + \hat{H}_{SQUID} + \hat{H}_{COUPL} \]
Hamiltonian of the coupled qubits

\[ \hat{H} = h \nu_S \hat{\sigma}_z^S + h \nu_T \hat{\sigma}_z^T + \frac{1}{2} h g \left( \hat{\sigma}_S^+ \hat{\sigma}_T^- + \hat{\sigma}_S^- \hat{\sigma}_T^+ \right) \]

\[ h g = \frac{E_{c,c}}{2} - E_{c,j} \cos(\delta/2 + \mu \tan(\delta)) \]

**Capacitive coupling**

\[ E_{c,c} = (1 - \lambda) \sqrt{\frac{E_C^S}{h \nu_p}} h \nu_p \]

\[ \lambda = \frac{(C_1^T - C_2^T)}{(C_1^T + C_2^T)} \]

**Josephson coupling**

\[ E_{c,j} = (1 - \mu) \sqrt{\frac{E_C^S}{h \nu_p}} E_{J}^T/2 \]

\[ \mu = \frac{(E_{J,1}^T - E_{J,2}^T)}{E_J^T} \]
We consider $\lambda = \mu = 41.6\%$.
We consider $\lambda = 37.7\%$ and $\mu = 41.6\%$.

If transistor was symmetric ($\lambda = \mu = 0$) coupling would be zero.
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- **Two different qubits**

- **Strong tunable coupling** between a charge and phase qubit (x18)

- **Zero coupling and non-zero coupling**