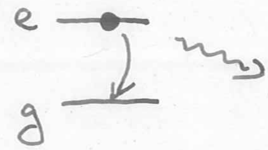
4.10 Control & Characterization of SC qubits

- Previous section: Measurement (intentional or unintentional!) as a mechanism causing decoherence.
- More generally: „The environment is watching" → Various sources of noise causing decoherence. See [4.11].

- Distinguish two types:



- Energy relaxation
  → Metric: Lifetime T_1 of excited state.

Spontaneous noise-induced excitation much less likely in SC circuits.

- Dephasing
  → Metric: Dephasing time T_2

- How to characterize?

  General approach: Initialize qubit in well-controlled state and monitor average state evolution for different protocols.

First step: Controlling the state of a qubit

Want: $|\psi_{in}\rangle$ —$\boxed{\mathcal{U}}$— $|\psi_{out}\rangle$ for general unitary $\mathcal{U}$.

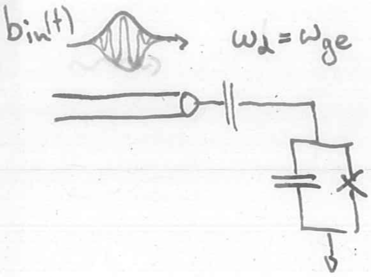
⇒ Decompose $\mathcal{U}$ into rotations of the Bloch vector —$\boxed{R_i(\vartheta)}$— about axis $i \in \{x, y, z\}$ by angle ϑ.

$$R_i(\vartheta) \equiv e^{-i\vartheta/2\,\sigma_i} = \cos\frac{\vartheta}{2}\,\mathbb{1} - i\sin\frac{\vartheta}{2}\,\sigma_i$$

Show as an exercise using $e^A = \sum \frac{A^n}{n!}$ and $\sigma_i^2 = \mathbb{1}$

Implementation: Turn on Hamiltonian $\tilde{H}/\hbar = \frac{\Omega}{2}\sigma_i$ for time $\tau = \frac{\vartheta}{\Omega}$

Rabi rate



$$b_{in}(t) = \beta_{in}(t)\, e^{-i(\omega_{ge}t + \varphi)}$$

phase

pulse envelope

Carrier fequency

$$H_d(t) = \sqrt{\gamma}\,\beta_{in}(t)\left(\sigma^- e^{i(\omega_{ge}t+\varphi)} + \sigma^+ e^{-i(\omega_{ge}t+\varphi)}\right)$$

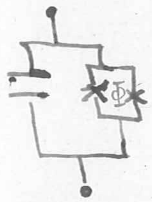
assume to be real-valued for simplicity.

In the interaction picture (rotating frame):

$$\tilde{H}_d = e^{\frac{iH_0 t}{\hbar}} H_d\, e^{\frac{-iH_0 t}{\hbar}} = \underbrace{\sqrt{\gamma}\,\beta_{in}}_{\equiv \frac{\Omega}{2}} \underbrace{\left(\sigma^- e^{+i\varphi} + \sigma^+ e^{-i\varphi}\right)}_{= \begin{cases} \sigma_x, & \varphi = 0 \\ \sigma_y, & \varphi = \frac{\pi}{2} \end{cases}}$$

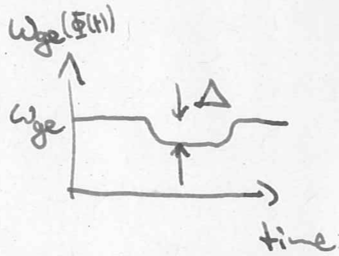
$\Rightarrow$ Driving the qubit resonantly with a field of controlled phase and amplitude allows for implementing arbitrary rotations about x and y axis.

How about z?



$$\omega_{ge} \to \omega_{ge}(\Phi) = \omega_{ge} + \Delta(\Phi)$$

detuning



Detune qubit frequency for controlled time by applying magnetic flux pulse.

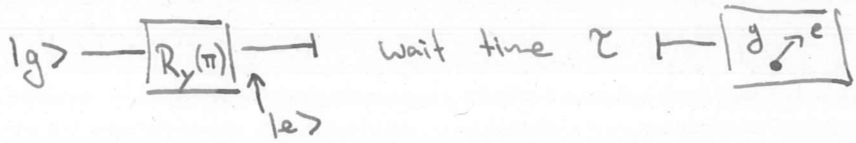
$$\Rightarrow \tilde{H}_d/\hbar = \frac{\Delta}{2}\sigma_z$$

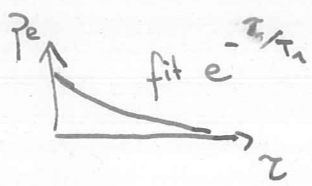
Note: z rotations can also be realized "virtually" by updating the reference frame of all subsequent x, y rotations (compare McKay et al., PRA (2017))

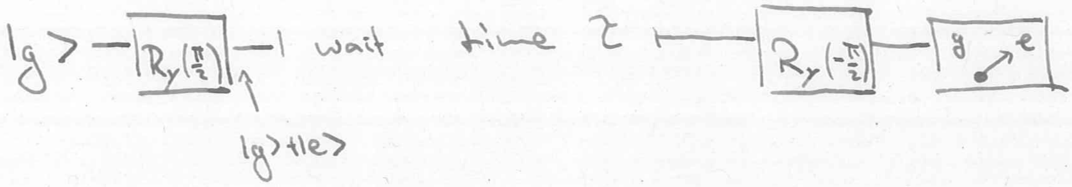
See slides for technical details of realization.

- Control lines on the chip
- Generation of pulses

Protocols to measure T_1, T_2 :







Ramsey experiment

Discussion see slides
- state of the art, "T_1 limit" of T_2, echo, off-resonant drive.

4.11 Sources and mitigation of noise

Discussion see slides.