

T_1 and T_2 time contributions in superconducting circuits

The longitudinal and transverse relaxation rates are given by their inverse time scales. Within the Bloch-Redfield description, the transverse relaxation is given by the longitudinal relaxation and dephasing. [8]

$$\Gamma_1 = \frac{1}{T_1} \tag{1}$$

$$\Gamma_2 = \frac{1}{T_2} = \frac{\Gamma_1}{2} + \Gamma_\varphi \tag{2}$$

Strictly speaking, due to $1/f$ noise, the decay functions of the off-diagonal terms are non-exponential and the system does not fall into the Bloch-Redfield regime. However for $T_\varphi \gtrsim T_1$, the decay can be approximated by an exponential function. If there is no pure dephasing, it holds that $T_2 = 2T_1$, otherwise we have $T_2 \leq 2T_1$. In the following we give an overview of noise contributions for superconducting qubits, which we could implement in CircuitQ.

1 T_1

Contribution	Formula	Remarks
Spontaneous emission	$T_1 = \frac{12\pi\epsilon_0\hbar c^3}{d} \frac{1}{\omega_q^3}$ [7]	$d = 2eL$: Dipole moment with $L \sim 15 \mu\text{m}$ [7] ω_q : Qubit frequency For transmon, contribution to $T_1 = 0.3 \text{ ms}$ [7]
Quasiparticle tunneling	$T_1 = \left(\sum_j \langle g, q_{o,j} e, q_{o,j} + e \rangle ^2 S_{qp,j}(\omega_q) \right)^{-1}$ [4, 1]	$S_{qp,j}(\omega_q) = x_{qp} \frac{8E_{J,j}}{h} \sqrt{\frac{8\Delta}{\hbar\omega_q}}$ [10] $E_{J,j}$: Josephson energy of the j -th junction $x_{qp} = 10^{-7}$ [9, 2] $\Delta \approx 1.76 \cdot k_B T_c$: superconducting gap [6] $T_c \approx 1.2 \text{ K}$: critical temperature in aluminum [5]
Charge noise	$T_1 = \left(\sum_i \frac{S_Q(\omega_q)}{\hbar^2} \left \langle e \hat{V}_i g \rangle \right ^2 \right)^{-1}$ [10]	$\hat{V}_i = \left(\hat{Q}^T C^{-1} \right)_i$: voltage operator \hat{Q} : charge operator vector with the charge-variables on the rows. $S_Q(\omega_q) = A_Q^2 \left(\frac{2\pi \cdot 1 \text{ Hz}}{\omega_q} \right)^{\gamma_Q}$: noise spectral density with $A_Q^2 = (10^{-3}e)^2/\text{Hz}$ and $\gamma_Q \approx 1$ [8]
Flux noise	$T_1 = \left(\sum_i \frac{S_\Phi(\omega_q)}{\hbar^2} \left \langle e \hat{I}_i g \rangle \right ^2 \right)^{-1}$ [10]	\hat{I}_i : current operator, which includes the sum of all $\frac{\Phi_i - \Phi_j}{L_{ij}}$ and $I_{C,ij} \sin \frac{\Phi_i - \Phi_j}{\Phi_0}$ terms in the circuit that correspond to a closure branch. $I_{C,ij} = \frac{2e}{h} E_{J,ij}$: critical current $S_\Phi(\omega_q) = A_\Phi^2 \left(\frac{2\pi \cdot 1 \text{ Hz}}{\omega_q} \right)^{\gamma_\Phi}$: noise spectral density with $A_\Phi^2 \approx (10^{-6}\Phi_0)^2/\text{Hz}$ and $\gamma_\Phi \approx 0.8 - 1$ [8]
Purcell effect	We don't include the purcell effect as we exclude external control and read-out circuitry from our analysis.	For transmon, contribution to $T_1 \sim 16 \mu\text{s}$ [7]

Table 1: Overview of the noise contributions to T_1 .

2 T_2

The pure dephasing contributions listed in table 2 should vanish at the sweet spot. External parameters are used to perform gates, prepare states or tune the qubit. These parameters are used to manipulate the qubit and are no fundamental components. Therefore we do not consider these contributions for now.

Contribution	Formula	Remarks
Offset charge noise (pure dephasing)	$T_2 \sim \frac{\hbar}{A_q} \left \frac{\partial E_q}{\partial q_{off}} \right ^{-1}$ [7]	This formula can be used for small fluctuations and small frequencies $A_q = 10^{-4}e - 10^{-3}e$: noise amplitude E_q : qubit energy
Offset flux noise (pure dephasing)	$T_2 \sim \frac{\hbar}{A_\phi} \left \frac{\partial E_q}{\partial \phi_{off}} \right ^{-1}$ [7]	This formula can be used for small fluctuations and small frequencies $A_\phi = 10^{-6}\Phi_0 - 10^{-5}\Phi_0$: noise amplitude

Table 2: Overview of the noise contributions to T_2 .

References

- [1] Instead of implementing the sinus-operator $\sin(\hat{\varphi}_j/2)$, we calculated it's action directly by considering the bracket between ground state and excited state that is shifted by one elementary charge.
- [2] The formula given in reference [3] seems to underestimate the density of quasiparticles.
- [3] G. Catelani, J. Koch, L. Frunzio, R. J. Schoelkopf, M. H. Devoret, and L. I. Glazman. Quasiparticle relaxation of superconducting qubits in the presence of flux. *Phys. Rev. Lett.*, 106:077002, Feb 2011. URL: <https://link.aps.org/doi/10.1103/PhysRevLett.106.077002>, doi:10.1103/PhysRevLett.106.077002.
- [4] G. Catelani, R. J. Schoelkopf, M. H. Devoret, and L. I. Glazman. Relaxation and frequency shifts induced by quasiparticles in superconducting qubits. *Phys. Rev. B*, 84:064517, Aug 2011. URL: <https://link.aps.org/doi/10.1103/PhysRevB.84.064517>, doi:10.1103/PhysRevB.84.064517.
- [5] John F. Cochran and D. E. Mapother. Superconducting transition in aluminum. *Phys. Rev.*, 111:132–142, Jul 1958. URL: <https://link.aps.org/doi/10.1103/PhysRev.111.132>, doi:10.1103/PhysRev.111.132.
- [6] Rafael M. Fernandes. *Lecture Notes: BCS theory of superconductivity*. URL: https://portal.ifi.unicamp.br/images/files/graduacao/aulas-on-line/fen-emerg/lecture_notes_BCS.pdf.
- [7] Jens Koch, Terri M. Yu, Jay Gambetta, A. A. Houck, D. I. Schuster, J. Majer, Alexandre Blais, M. H. Devoret, S. M. Girvin, and R. J. Schoelkopf. Charge-insensitive qubit design derived from the cooper pair box. *Phys. Rev. A*, 76:042319, Oct 2007. URL: <https://link.aps.org/doi/10.1103/PhysRevA.76.042319>, doi:10.1103/PhysRevA.76.042319.
- [8] P. Krantz, M. Kjaergaard, F. Yan, T. P. Orlando, S. Gustavsson, and W. D. Oliver. A quantum engineer's guide to superconducting qubits.

Applied Physics Reviews, 6(2):021318, June 2019. arXiv:1904.06560, doi: 10.1063/1.5089550.

- [9] C. Wang, Y. Y. Gao, I. M. Pop, U. Vool, C. Axline, T. Brecht, R. W. Heeres, L. Frunzio, M. H. Devoret, G. Catelani, L. I. Glazman, and R. J. Schoelkopf. Measurement and control of quasiparticle dynamics in a superconducting qubit. *Nature Communications*, 5(1):5836, 2014. URL: <https://doi.org/10.1038/ncomms6836>, doi:10.1038/ncomms6836.
- [10] Fei Yan, Simon Gustavsson, Archana Kamal, Jeffrey Birenbaum, Adam P Sears, David Hover, Ted J. Gudmundsen, Danna Rosenberg, Gabriel Samach, S. Weber, Jonilyn L. Yoder, Terry P. Orlando, John Clarke, Andrew J. Kerman, and William D. Oliver. The flux qubit revisited to enhance coherence and reproducibility. *Nature Communications*, 7(1):12964, 2016. URL: <https://doi.org/10.1038/ncomms12964>, doi: 10.1038/ncomms12964.