

Practical Quantum Computing: qubit noise

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- 1 Simplified noise description
- 2 Qubit characterization experiments

Sources of noise for superconducting qubits:

- **Charge noise** — on the metal surface, inside dielectrics, fluctuating two-level states
- **Magnetic flux noise** — stochastic flipping of spins
- **Photon-number fluctuation** — residual microwave fields, shifts of resonance frequency
- **Quasiparticle poisoning** — internal excitations in superconductor
- **Summary:** unavoidable interaction with environment

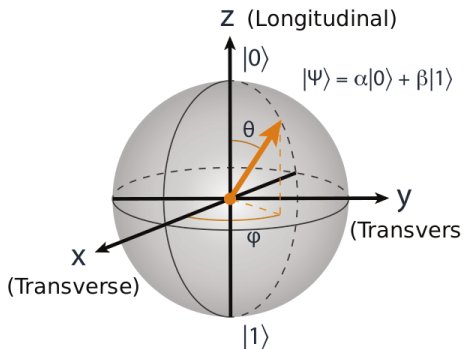
references: *"A Quantum Engineer's Guide to Superconducting Qubits"*

<https://arxiv.org/abs/1904.06560>; Nielsen & Chuang Chap. 7.7.2;

Nielsen & Chuang Chap. 8.3 (examples of quantum noise)

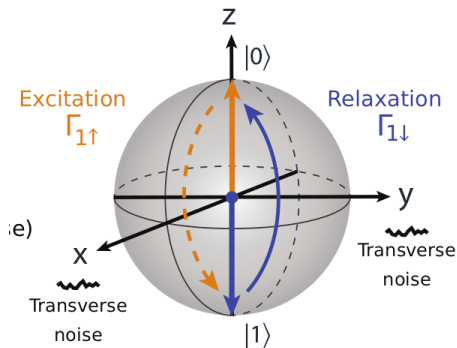
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(a) Bloch sphere



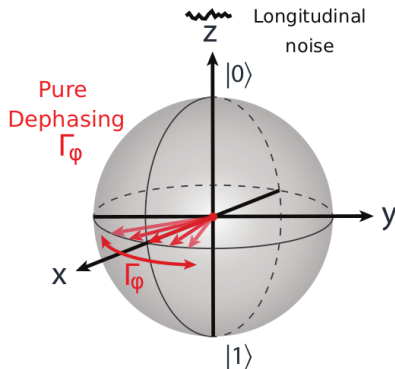
- north pole, south pole, longitudinal axis, transverse axes
- Bloch vector stationary in the rotating frame
- pure state on surface, mixed states in interior

(b) Longitudinal relaxation



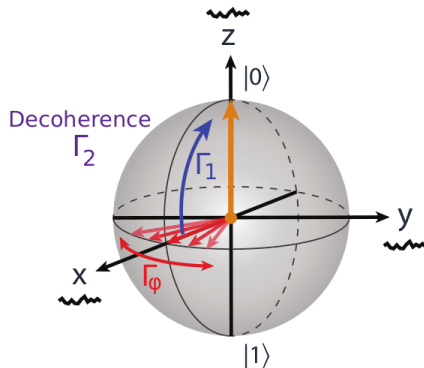
- energy exchange drives transitions $0 \leftrightarrow 1$
- longitudinal relaxation comes from transversal noise
- characteristic time scale T_1 (energy decay)

(c) Pure dephasing



- longitudinal noise fluctuates the qubit frequency
- Bloch vector rotation in xy-plane is stochastic
- characteristic decay time T_ϕ (loss of phase information)

(d) Transverse relaxation



- uniform noise in all directions – depolarizing process
- causes both relaxation and decoherence
- $1/T_2 = 1/(2T_1) + 1/T_\phi$
- fundamental limit: $T_2 \leq 2T_1$

Bloch-Redfield model: Synthesis

Initial density matrix of a pure state:

$$\rho(0) = \begin{pmatrix} |\alpha|^2 & \alpha\beta^* \\ \alpha^*\beta & |\beta|^2 \end{pmatrix}$$

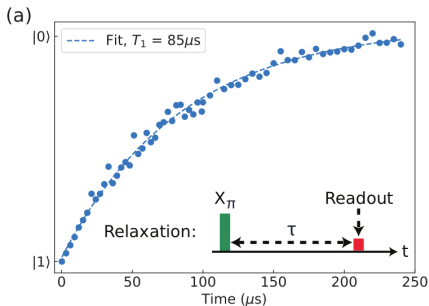
Time evolution influenced by T_1 (Γ_1) and T_2 (Γ_2) noise:

$$\rho(t) = \begin{pmatrix} 1 + (|\alpha|^2 - 1) e^{-\Gamma_1 t} & \alpha\beta^* e^{-\Gamma_2 t} e^{-i\delta\omega t} \\ \alpha^*\beta e^{-\Gamma_2 t} e^{i\delta\omega t} & |\beta|^2 e^{-\Gamma_1 t} \end{pmatrix}$$

- assumes noise is weakly coupled to qubit (short correlation times)
- $\Gamma_1 = 1/T_1$ and $\Gamma_2 = 1/T_2$
- $\delta\omega$ is the intentional detuning with respect to the rotating frame

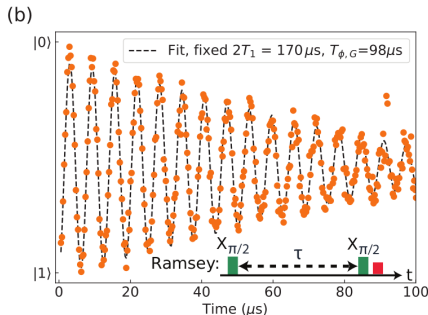
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T_1 relaxation time



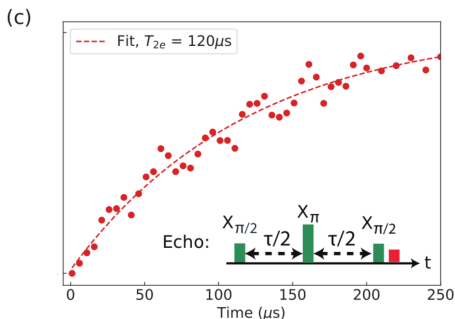
- characteristic exponential decay time $P(1) \propto e^{-t/T_1}$
- initiate with X pulse (excite to $|1\rangle$), delay by τ , measure

Ramsey experiment (T_2^*)



- experiment with two separated $X_{\pi/2}$ pulses; running on small intentional detuning f
- convolution of decay with oscillation $P(1) \propto e^{-t/T_2^*} \cos(2\pi ft)$
- measures T_2^* which includes pure dephasing **and** inhomogeneous spatial/temporal noise broadening
- sequence: initiate $R_x(\pi/2)$, delay τ , add detuning $R_z(2\pi f\tau)$, rotate back $R_x(\pi/2)$, measure

Spin Echo experiment (T_{2e})



- adding a refocusing π -pulse cancels slowly fluctuating (low-frequency) decoherence
- characteristic echo time T_{2e} closer to the theoretical T_2 limit ($T_{2e} > T_2^*$)
- sequence: initiate $R_x(\pi/2)$, delay $\tau/2$, apply inverting pulse X , delay $\tau/2$, rotate back $R_x(\pi/2)$, measure

Summary & Outlook

- **Theory:** Qubit coherence is fundamentally limited by energy relaxation (T_1) and pure dephasing (T_ϕ), combining into total transverse relaxation (T_2).
- **Experiment:** We characterize these limits using inversion recovery (T_1), Ramsey interferometry (T_2^*), and Spin Echo (T_{2e}).
- **The Engineering Challenge:** How do we isolate qubits from environmental noise while maintaining the ability to control and couple them? (e.g., dynamic decoupling, better materials, error correction).