Measuring Qubit Decoherence
T1 decay and T2 Spin Echoes
Quantum Challenge Berlin 2020

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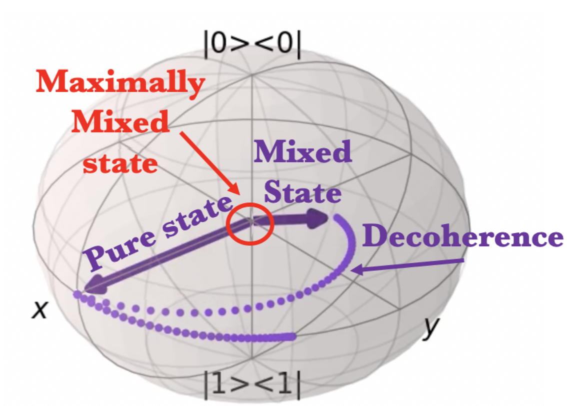
1 Model and visualization of Decoherence:

One of the biggest limitations of quantum systems is the amount of time they are able to maintain a good quality quantum behavior. The process of losing the relative phases between states is called dephasing, or decoherence. In a perfect world, quantum systems would be totally isolated from the environment. However, this is not possible in real life: after all, we will disturb the system when inputting the signals necessary to control them.

Coherence times at the moment range in the scale of hundreds of microseconds (Qiskit SC qubits, Rigetti systems) to milliseconds (trapped ions). Even though we reduce noise rates as technology advances, getting to know decoherence times precisely is an important task in order to design algorithms that work as desired.

To describe recoherence technically, we use a density matrix approach:



Loosely speaking, the relative quantum phases between states are encoded in the off-diagonal terms the density matrix, and we say that there is coherence between states. On the other hand, a state with zero off-diagonal terms is said decohered. **For example,** a system in the superposition state $|\phi\rangle = 1/\sqrt{2}(|0\rangle + e^{i\phi}|1\rangle)$ has the following density matrix:

$$\rho = |\phi\rangle\langle\phi| = \frac{1}{2}\begin{bmatrix} 1 & e^{i\phi} \\ e^{-i\phi} & 1 \end{bmatrix}$$

Physicists have identified two different timescales when describing decoherence. **Note:** The following notation is borrowed from Magnetic Resonance jargon, where they work with spins. However, as both spins and qubits are two-level systems, we can use them interchangeably.

1.1 Amplitude Damping or T1:

This is the exponential decay of any state towards the ground-energy eigenstate (that we call $|0\rangle$):

$$\rho = \begin{bmatrix} \rho_{00} & \rho_{01} \\ \rho_{01}^* & \rho_{11} \end{bmatrix} \xrightarrow[T1]{t} \begin{bmatrix} \rho_{00} + (1 - e^{-t(T1)})\rho_{11} & \rho_{01}e^{-t/T1} \\ \rho_{01}^* e^{-t/T1} & \rho_{11}e^{-t/T1} \end{bmatrix} \xrightarrow{\infty} |0\rangle \langle 0|$$

Notice that T1 removes any coherence between $|0\rangle$ and $|1\rangle$.
T1 sets the characteristic timescale for the decay process. Notice that after setting the state in $|1\rangle \langle 1|$ the probability of it remaining on it is: $\mathrm{P}(|1\rangle, t) = \mathrm{Tr}[|1\rangle \langle 1| \rho(t)] = e^{-t/T1}$. Thus, we can measure T1 using the following procedure:

1. Apply a π-pulse on $|0\rangle$ and get $|1\rangle$
2. Wait a time t
3. Measure, in the $\{|0\rangle, |1\rangle\}$ basis
4. Repeat several times to get $\mathrm{P}(|1\rangle, t)$

Note that T1 affects both the off-diagonal and the on-diagonal terms

1.2 Transversal Decay or T2:

There are other noise processes that only affect the off-diagonal terms. This means that the relative probabilities between $|0\rangle$ and $|1\rangle$ remain untouched, and it is just their phase what is erased. This process moves states in planes transversal to the $|0\rangle \leftrightarrow |1\rangle$ line.
Under dephasing noise, the state of the qubit evolves as:

$$\rho = \begin{bmatrix} \rho_{00} & \rho_{01} \\ \rho_{01}^* & \rho_{11} \end{bmatrix} \xrightarrow[T2]{t} \begin{bmatrix} \rho_{00} & \rho_{01}e^{-t/T2} \\ \rho_{01}^* e^{-t/T2} & \rho_{11} \end{bmatrix} \xrightarrow{\infty} \frac{1}{2}(|0\rangle \langle 0| + |1\rangle \langle 1|)$$

Note: T1 and T2 inequalities

- $T1 > T2$: This happens because T1 does always imply T2, but the opposite is not true. This is because there are many processes that cause T2 decays, but less that also cause T1.
- $T2 > T2*$: T2* is the effective version of T2, the result that we get doing a naÃ¯f measurement (the one without echoes). In out case, T2* being smaller than T2 can be seen in the fact that having many qubits precessing at slightly different frequencies cancel each other when averaging and leaves us with an effective value much closer to the centre.

To measure T2*:

1. Apply a $\pi/2$-pulse on $|0\rangle$ and get $|+\rangle$
2. Wait a time t.
3. Measure, in the $\{|0\rangle, |1\rangle\}$ basis by applying another $\pi/2$-pulse.
4. Repeat several times.

The qubits spreading through the equeator yield a T2* really low (2 orders of magnitude). This is why we use th Spin or Hahn echo:

- Introduce a π-pulse at t/2.

The π-pulse forces the qubits to refocus again when we make the actual measurements, thus avoiding the effects of them spreading. This way, we obbtain T2.

2 The `qiskit.pulse()` module:

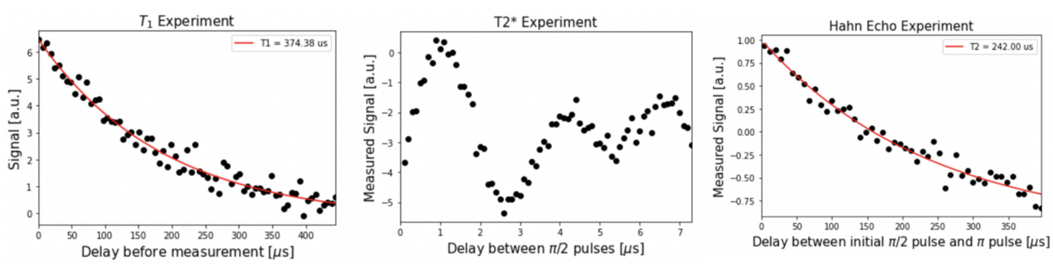
The Qiskit hardware provides a time sampling rate down to 0.22ns. This is enough to get a an appropriate resolution in the pulse schedules that are implemented. In other words, a 0.22ns time slicing allows to visualize the Rabi Oscillations and the echo processes really well, because the qubit's detuning precession frequency is in the order of MHz.

Note on Detuning: The free IBM qubits precess at really high frequencies of around $w \simeq$ 5GHz, which is the energy diference between their two levels. However, as the dynamics are stimulated by external pulses, it makes sense to move to a Frame of Reference static with the pulses. The pulses have a frequency $w_0 \sim w$, to produce resonance. Thus, the qubit will effectively rotate at a frequency $\Delta = w - w_0 \sim$ Mhz.
This change of Frame of Reference is sometimes called the Rotating Wave Approximation.

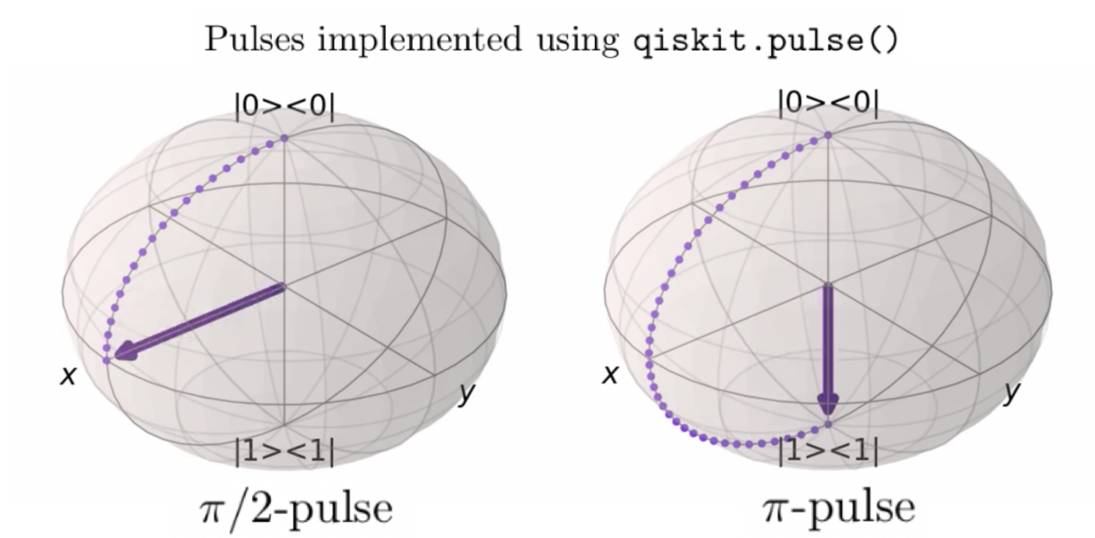
I have implemented and used the following pulses. To do so, I have tracked Rabi Oscillations to find the amplitude of the excitation pulse, driven at resonance, producing the desired transitions in a fixed time Δt.

3 Experimental results:

After running the experiments at **`ibmq_armonk`** quantum processor, we get the following results:



$\pi/2$-pulse Pulses implemented using `qiskit.pulse()`



References:

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- Rabi oscillations, Ramsey fringes and spin echoes in an electrical circuit, *D. Vion1, A. Aassime1, A. Cottet, et al.*
- Medium magazine: "The benefits of high-resolution pulses for quantum computers".
- IBM docs.: "Get to the heart of real quantum hardware".
- Spin echoes, *E. L. Hahn*