Overview of Prominent Decoherence Mechanisms in Superconducting Qubits

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Abstract

In recent years, superconducting qubits have become the primary candidate for quantum computing applications, yet an increase in coherence time is necessary to exploit the full potential of this technology. In this paper we provide a short overview of prominent sources of decoherence in superconducting qubits. Quasiparticle tunneling across Josephson Junctions is discussed as well as relevant experiments from Ristè et al and Serniak et al, followed by two-level system noise and a subgroup of said noise termed *quasiparticle* two-level system noise.

Introduction

A quantum bit or qubit is defined as the two states of a quantum system [1] and are used to store and process quantum information analogously to how bits store and process information in an everyday, standard, computer. Though quantum computers possess many advantages over their classical counterparts at small scales, we are still not able to control the various mechanisms that introduce noise into the system to take advantage of the full capabilities of larger arrays of qubits. Noise can lower the coherence time of the qubit, which is how long a qubit maintains a certain state before the information is irreversibly lost.

At present, macroscopic superconducting electrical circuits with quantum mechanical degrees of freedom are the leading candidate for fault tolerant quantum computation. We will refer to these simply as superconducting qubits. The reasons for this leadership status despite other architectures with decades of prior work, atomic clocks for instance, is due to the ease of fabrication (semiconductor processing), control (leveraging radar/wireless technology), and ease of operation from breakthroughs in commercial cryogenic systems. Despite more than a six orders of magnitude improvement in the coherence time of electrical circuits since debuting in the 1980s, and the aforementioned advantages over their competition, nonequilibrium Quasiparticles (QPs) (page 4) and Two-level Systems (TLS) (page 7) still contribute significantly to decoherence in superconducting qubits. In addition, De Graaf et al have recently found evidence of a phenomenon where QPs become trapped in a potential well formed by local minima of the superconducting order parameter (Δ), thus creating Quasiparticle Two-level Systems (qTLS) which behave differently to traditional noise and could be a significant source of qubit relaxation or excitation [2]. Quantum systems are very sensitive to different types of noise; thus, to make further advances in quantum computing technology, it is crucial that we can identify and understand the mechanisms that lead to this noise

LC Circuit as a Superconducting Qubit

In order to understand how macroscopic circuits could posses quantum mechanical degrees of freedom (i.e have what are called mesoscopic properties), we will examine a typical LC circuit (an example used in [3]). A typical LC circuit may have an inductance L=1nH and capacitance C=10pF which result in a resonant frequency of about 1.6GHz. Since the dimensions of the circuit are of only a few hundred micrometers (much less than the circuit's operating wavelength), this puts our circuit in the lumped element limit, and we can describe it using the collective degree of freedom Φ. For Φ to be treated as a quantum mechanical variable, the width of the energy levels must be smaller than their separation, which puts a constraint on the damping of the oscillator. This damping can be expressed by the quality factor Q, which is a ratio of the energy being stored to the energy being dissipated. Q needs to be $\gg$1 which can be achieved by using a superconductor as the wire of the inductor. This is an example of a mesoscopic device; however, it falls in the category of harmonic oscillator, which means that different energy levels are not individually addressable, and it would be impossible for us to restrict the system to only two states as a qubit requires. In order to address individual quantum states, we must introduce a non-linear component to our circuit (thus, making it an anharmonic circuit). A Josephson junction (JJ) is a device that consists of an insulator "sandwiched" between two super conductors and can act as a non-dissipative and non-linear inductance at temperatures in the millikelvin range, where temperatures are sufficiently low for electrons to condense below the Fermi energy and form Cooper pairs [1]. Cooper pairs are pairs of electrons bound together at low temperatures due to electron-phonon interactions.

The Transmon

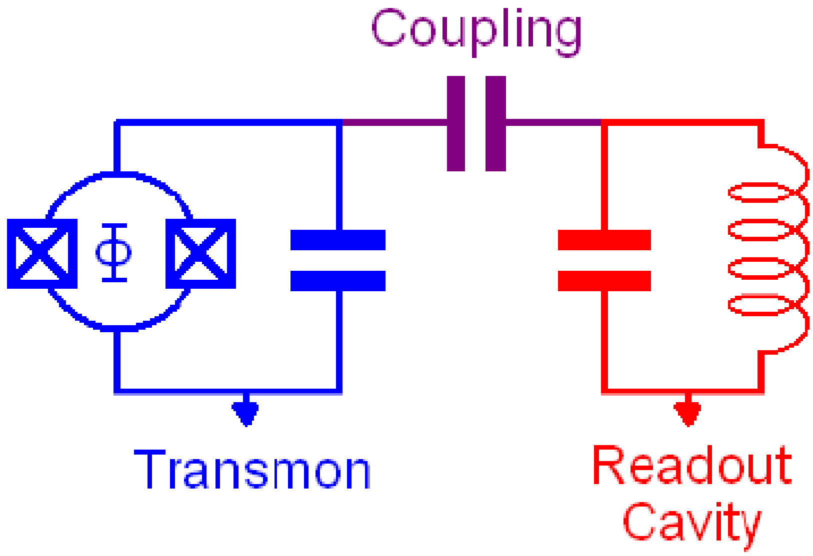

Figure 1: Circuit schematic of a transmon qubit capacitively coupled to a linear readout resonator. In this figure, there are two JJs in parallel (each X is a JJ); this is known as a SQUID loop. *Adapted from [1].*

If we shunt the circuit described in the previous section (which has an eneryg E_j stored in the JJ) with a large enough capacitance such that the electrostatic energy (stored in capacitance $E_c = e^2/2C$) is significantly reduced ($E_j/E_c >> 1$), then we remove the sensitivity of the qubit frequency to charge noise. In this regime, the qubit is called a transmon. The increased capacitance influences two parameters, the anharmonicity (difference in energy between successive excitations) and the charge dispersion (the degree to which the energy levels are dependant on the offset charge n_g). The advantage of the transmon comes from predicting that as E_j/E_c is increased, the charge dispersion decreases exponentially while the anharmonicity decreases only with a power law [1]. At values of $E_j/E_c = 50$, for example, the remaining charge dispersion is so small that conservative estimates predict dephasing times (T_2) due to charge noise in the order of seconds—a significant advantage over its predecessor, the Cooper Par Box (CPB), which had a T_2 limmited to $< 1\mu s$ [4]. The disadvantage here is that as the anharmonicity decreases, it becomes more difficult to selectively excite only one pair of levels. Thus, a more complex pulse, typically a DRAG pulse, must be applied instead of a simple Gaussian pulse.

Quasiparticles

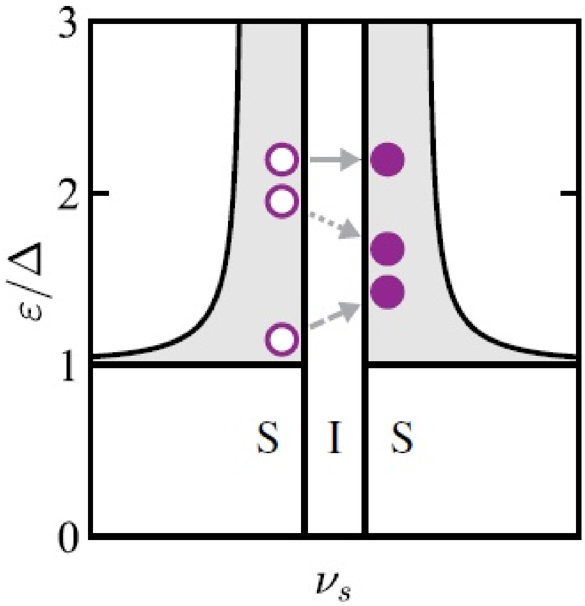

Figure 2: Illustration of the different mechanisms by which QPs can alter a qubit state. Density of states ν_s versus reduced energy ϵ/Δ is shown in the leads of a superconductor-insulator-superconductor (SIS) JJ. A solid arrow corresponds to an interband transition, dotted line to excitation and dashed line to relaxation of the qubit. *Adapted from [5].*

A quasiparticle (QP) is a disturbance that behaves like a particle in a medium, and is regarded as such. An electron which travels through a semiconductor, for example, is disturbed in a complex way by other electrons and nuclei. Its behaviour can be approximated by an electron with a different effective mass that travels undisturbed in the same semiconductor. This electron with different effective mass would be called an electron QP [6]. Electron QPs are a common source of noise in superconducting qubits, and many are generated from the decoupling of Cooper pairs (which is not uncommon due to their small binding energy, $\sim 10^{-3}$ eV [7]). QP tunneling across the JJ is a well-studied phenomenon which can cause qubit excitation or relaxation (a bit flip)(see Fig 2), and even though making Ej/Ec $\gg 1$ exponentially suppresses the sensitivity of the qubit to charge parity and background charge fluctuations, recent theory predicts QP tunneling is still a relevant source of relaxation and pure dephasing [8] [9].

Using Ramsey Interferometry to Find Evidence of Charge Parity Switches

For evidence that QP tunneling is actually accruing, one may look to detect a change in qubit parity for which it suffices to perform a typical Ramsey experiment. A Ramsey sequence is a method that can be used for finding the T_2 and the resonant frequency of a qubit—the frequency needed to drive the qubit from $|0\rangle$ to $|1\rangle$. The sequence consists of two $\pi/2$ pulses separated by an intentional and variable delay (t) followed by a measurement of the qubit in the 0/1 basis. Introducing a known frequency detuning to the qubit pulses results in a procession around the Z-axis of the Bloch sphere at a constant rate, manifesting a sinusoidal oscillation in the output qubit basis state in the measurements. The value of an intentional detuning is a precision measurement of the qubit frequency limited by the coherence of the device. The frequency of oscillation should be the same as the detuning. Thus, the difference between detuning frequency and the measured frequency of oscillation is the error in our measurement and can be used to make a previous frequency sweeping measurement more precise. In addition, because the sinusoid decays proportional to $e^{T_2/t}$, we can find T_2 from the fit. If there is a change in parity during these measurements, then our output will show two decaying sinusoids instead of one because each parity has a different frequency (see Fig 3).

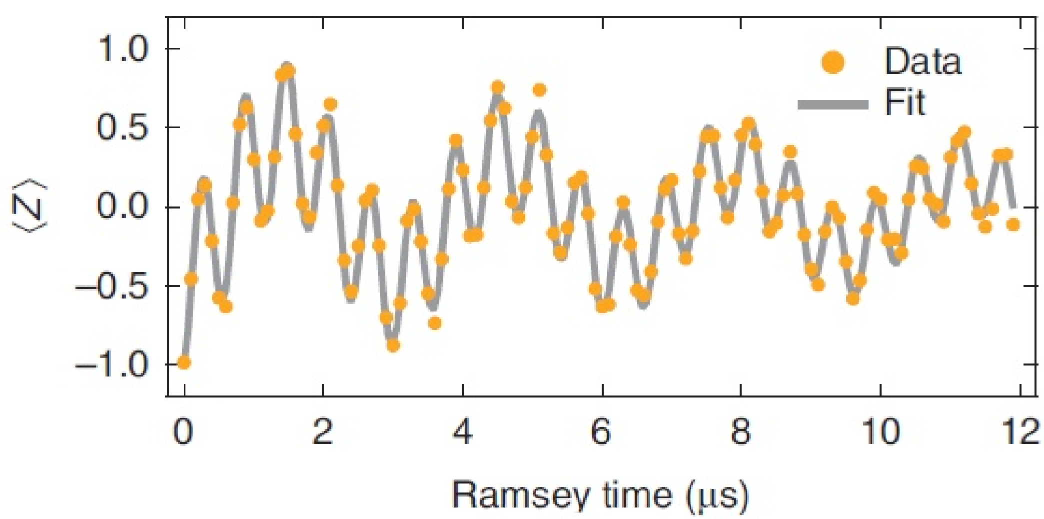

Figure 3: Ramsey fringe experiment (dots) and best-fit sum of two decaying sinusoids (curve). If there was no change in parity, there would only be a single decaying sinusoid. *Adapted from [4].*

Charge Parity Dependent Decoherence Mechanisms

To date, only upper and lower bounds on QP tunneling rates have been placed in transmon qubits [10] [11], while the effect of QP tunneling on transmon decoherence remains unexplored. For further improvements to be made, it is important to measure the time scale of QP tunneling and how it affects qubit decoherence. In order to acquire this time scale, Ristè et al developed a technic to measure QP tunneling in real time through repeated measurements of the charge parity by Ramsey interferometry [4]. To map quasiparticle charge parity into qubit basis states (0 and 1), we modify the Ramsey sequence as follows (see Fig 4). We begin by initializing the qubit in $|0\rangle$ through repeated quantum non-demolition measurements of the qubit state. We then apply a $\pi/2$ pulse around the Y-axis of the Bloch sphere which creates an equal superposition state. The system is then allowed to evolve for a duration Δt where $\Delta t = \Delta f/4$ with Δf being the frequency difference between the even and odd charge (QP) parity states, to maximally separate charge parity on the Bloch sphere conditioned on qubit state. To complete the mapping between charge parity and qubit state, we apply a final $\pi/2$ pulse around the X-axis of the Bloch sphere and perform a projective qubit state measurment. In this protocol, charge parity maps into the qubit basis state as $|0\rangle \rightarrow$ even and $|1\rangle \rightarrow$ odd. By applying this method, Ristè et al found a tunneling characteristic time of 0.79 ms and concluded that an increase in decoherence time, T_1, of one order of magnitude (from microseconds to milliseconds) was possible.

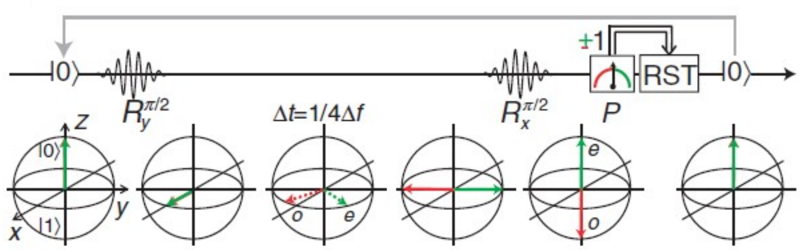

Figure 4: Illustration depicting Ristè et al's Ramsey-type experiment. The bloch spheres show how the state vectors corresponding to each frequency (red for odd, green for even) are altered as the experiment progresses. *Adapted from [4].*

An extension of this work by Serniak et al used this technique to determine the tunneling excitation rates (i.e. energy exchange from quasiparticles to the qubit) as well as relaxation rates and found that QP tunneling is responsible for $\sim 30\%$ of relaxation events and $\sim 90\%$ of excitation events [5]. This indicates that QP-induced excitation is responsible for the vast majority of the residual transmon excited-state population and suggests a higher energy distribution of nonequilibrium QPs than previously thought of (because the ratio of induced excitations vs. relaxation is greater than 1).

TLS and qTLS

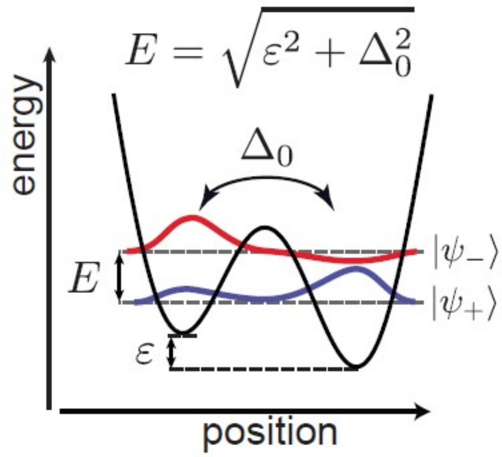

Figure 5: Representation of two-level defect according to STM. Δ_0 is the energy associated with the process of tunneling through the barrier separating the two wells, ϵ is the asymmetry energy and E is the energy difference between the TLS eigenstates $|\psi_-\rangle$ and $|\psi_+\rangle$. *Adapted from [12]* .

Another important source of noise originates in the dielectric component of amorphous materials, known as two-level system (TLS) noise. These are surface defects with two states which have a difference in energy close to or on resonance with the qubit or resonator excitation energy. When such TLSs are coupled to the qubit or resonator, they can contribute significantly to dielectric loss and energy relaxation [12]. The Standard Tunneling Model (STM) portrays the TLSs as two minima in a double-well potential separated by a barrier. However, while STM is a good phenomenological model, it provides insufficient knowledge to actually remove TLS in superconducting devices. The remaining 'unknowns' in the problem are microscopic parameters such as particle mass, the charge of the tunneling entity and the size and form of the TLS potential. Though several frameworks have been developed that propose tunneling atoms, electrons, among others, none has been proven.

Recent studies by de Graaf et al have identified a subgroup of TLS which possess unique properties not accounted for by STM, namely: are highly coherent with a low reconfiguration temperature of $\sim 300mK$, and a non-uniform density of states [2]. The energy scaling of these TLS is similar to the expected energy scaling of the super conducting order parameter (Δ), which gives reason to believe fluctuations in Δ are responsible for this noise. Moreover, de Graaf suggests that the unique properties of these TLS could be explained if they were formed by QPs which became trapped in local Δ minima (Fig 6); thus, they refer to them as qTLS for quasiparticle TLS.

An important observation from this study is that the reshuffling of the energy landscape that occurs at $\sim 300mK$ is irreversible, as shown by spectral and temporal mapping of the

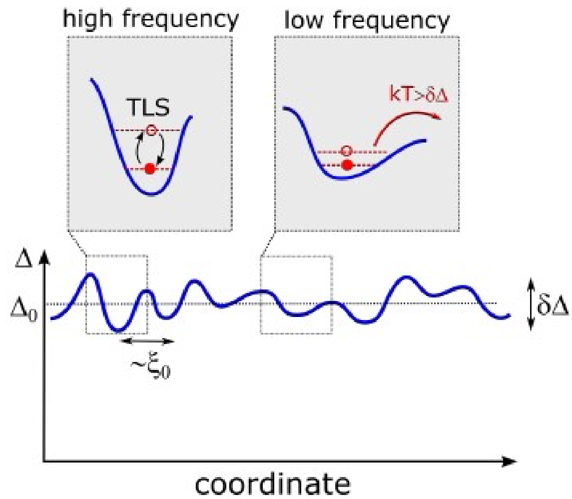

Figure 6: Illustration of Δ fluctuations forming wells with multiple bound states in which QPs may become trapped and form qTLS. *Adapted from [2].*

internal quality factor over several days (Fig 7). In these experiments, initial measurements were made at 10mK, and when the temperature was raised to 300mK, the TLSs now appeared at different frequencies than before. After returning the temperature back to 10mK, the energy landscape did not return to how it was originally. An unexpected outcome considering that 300mK is under the energy level splitting of the qTLS—which is 7GHz ($\sim 350mK$). This behaviour differs wildly from conventional TLS where thermal activation over the barrier is suppressed and the dynamics are governed by quantum tunneling through the barrier. Moreover, due to asymmetries in the traps, the transition between ground and first excited state have a strong dipole moment which results in a strong coupling to the resonator's quantum state. This, together with their relatively high coherence, suggests qTLS are a significant contributor to the overall TLS noise.

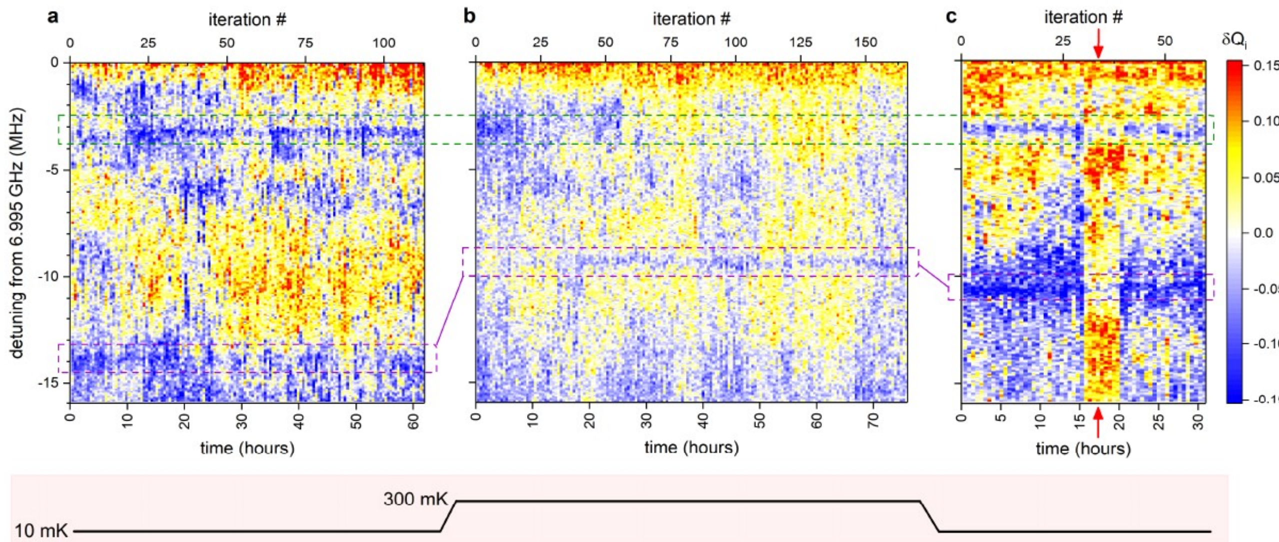

Figure 7: Spectral and temporal fluctuations of the internal quality factor and spectral reconfiguration of TLS, which is shown to be irreversible. Dashed boxes indicate two strongly coupled TLS. *Adapted from [2].*

For superconducting order fluctuations to efficiently trap quasiparticles, they must meet certain criteria. For example, being of a large enough frequency, as QPs in shallow traps recombine easily, and being elongated in the same direction of the particle's momentum (p_f). Further research might look to control such properties of the traps in order to make them less effective, thus reducing their impact on the coherence time.

Conclusion

Anharmonic LC circuits are an efficient mesoscopic device for use in quantum computers; however, their scalability and practicality are limited by noise. This noise largely originates from QP tunneling across the JJ and TLS, but, despite recent progress in the field, important aspects of their origin and mechanisms remain unsolved. Furthermore, the work of de Graaf et al exemplifies how there could still be unknown sources of noise that fall outside of the current models. Data from de Graaf's study suggests that a significant portion of the qTLSs exhibit strong coupling to the resonator device, which could make them a notable hurdle in the way of increasing coherence times. Another significant difficulty regarding qTLS is how they appear at different frequencies after the temperature is increased to 300 mK, which corresponds to energy lower than their energy splitting and cannot be explained by conventional TLS physics.

Once trapped in an effective local minimum of the Δ, QP recombination and equilibration becomes essentially impossible, and if these are close to a qubit, they can lead to long periods of qubit performance degradation. Confirming and expanding de Graaf's work might be the focus of future TLS research as most qTLS seem to be strongly coupled and thus could prove to be the most prominent source of decoherence. This research could look into suppressing delta fluctuations or manipulating their properties to make them less effective. In addition, investigating any possible connections to macroscopic properties of the materials used could be a useful tool when quantifying the degree to which this noise contributes to overall decoherence.

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