Correlating Decoherence in Transmon Qubits: Low Frequency Noise by Single Fluctuators

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We report on long-term measurements of a highly coherent, nontunable superconducting transmon qubit, revealing low-frequency burst noise in coherence times and qubit transition frequency. We achieve this through a simultaneous measurement of the qubit's relaxation and dephasing rate as well as its resonance frequency. The analysis of correlations between these parameters yields information about the microscopic origin of the intrinsic decoherence mechanisms in Josephson qubits. Our results are consistent with a small number of microscopic two-level systems located at the edges of the superconducting film, which is further confirmed by a spectral noise analysis.

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Today's prototype solid-state quantum computers built from superconducting qubits such as the transmon [1] are already capable of finding the electronic ground state of small molecules [2]. Their complexity keeps growing, while error rates of logical gate operations are already close to the threshold for some fault-tolerant quantum computing schemes [3,4]. However, the error probability due to random parameter fluctuations scales exponentially with the number of qubits, rendering the calibration of many-qubit systems difficult. The demand on stability and coherence of scaled-up quantum systems widens the focus of current research towards new decoherence mechanisms and fluctuations occurring on time scales of hours or even days.

To examine the stability of a transmon-type qubit, we perform long-term measurements of energy relaxation T_1, Ramsey T_2^{R}, and spin echo T_2^{E} coherence times, as well as the transition frequency ω_{q}. When these parameters are measured consecutively, inconsistencies are possible due to fluctuations. Here, we develop and employ a time-multiplexed pulse sequence pattern [see Fig. 1(a)] which allows us to acquire all qubit parameters simultaneously. Moreover, the interleaved pattern enables us to characterize correlations of qubit parameter fluctuations and coherence, which reveal a connection between noise at mHz frequencies and qubit dephasing.

Our long-term measurements reveal significant fluctuations in all qubit parameters, similar to earlier reports [5–7]. Figure 1(b) shows exemplary results of a continuous measurement over 19 hours. The qubit transition frequency displays telegraphic noise with multiple stationary points, which prompts our interpretation of the data in terms of an ensemble of environmental two-level systems (TLS) interacting with the qubit. TLS may emerge from the bistable tunneling of atomic-scale defects [8–10] which may reside within the amorphous AlO_x of the qubit's tunnel barrier or electrode surface oxides, but can also be formed by adsorbates or processing residuals on the chip surface [11,12]. Such defects may couple to the qubit by their electric dipole moments, leading to absorption of energy and fluctuations in qubit parameters. The TLS' parameters are broadly distributed and those TLS having transition frequencies near or at the qubit's resonance can cause dispersive frequency shifts [13], avoided level crossings [14–16], or resonances in qubit loss [5].

We attribute the observed fluctuations in qubit parameters to a sparse ensemble of environmental TLS close to the superconducting film edge and its interaction with thermal fluctuators. This model is supported by the power spectral density (PSD) of the observed frequency fluctuations. Complemented by a cross-correlation analysis, our data provide evidence for a small number of TLS which dominate dephasing if near resonant, while the $1/f$ noise background we also observe may emerge from a bath of more weakly coupled TLS [17]. We conclude that even single TLS on the edges of the superconducting films can dominate decoherence and cause random parameter fluctuations in superconducting qubits. We find that other sources of fluctuation, like temperature variations, critical current fluctuations, quasiparticle tunneling, or flux vortices play secondary roles in the presented experiment.

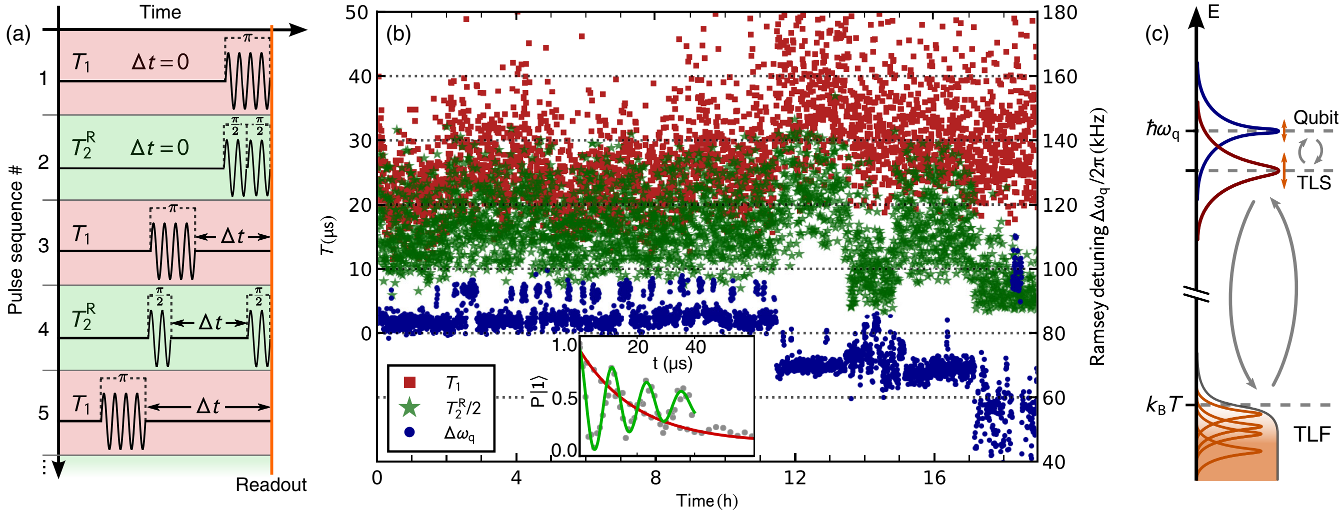

FIG. 1. (a) Measurement pattern: Single pulse sequences of different measurements (e.g., of T_1 and T_2^R) are interleaved, resulting in a simultaneous acquisition. The time Δt is the free evolution. The ratio between the number of pulses can differ, and spin echo pulses may be added. The inset in (b) shows an exemplary single trace with fits for T_1 (red), T_2^R and the Ramsey detuning $\Delta\omega_q$ (green). (b) Data taken over a course of 19 hours displays fluctuations in T_1 and T_2^R (red squares and green stars, left axis), and telegraphlike switching of the qubit frequency $\Delta\omega_q$ (blue dots, right axis). The time resolution corresponds to 10 s of averaging using the pattern shown in (a). For clarity, dephasing times are divided by two. With this measurement we reveal a connection between noise at mHz frequencies and qubit dephasing. (c) Illustration of how the frequency of a single TLS near resonance with the qubit fluctuates due to its coupling to thermally activated TLS (so-called TLF) at energies at or below $k_B T$ (orange shaded area). Depending on the detuning between qubit and TLS, this can cause positive or negative correlations between qubit coherence times and its resonance frequency.

Our interpretation of the data according to the interacting defect model [10,13,18] is further motivated by recent experiments, where the thermal switching of individual TLS in AlO_x Josephson junctions was measured directly [19]. Further, spectral diffusion of TLS was recently observed by monitoring the T_1 time of a tunable transmon qubit [5]. Our results confirm the findings that single TLS strongly affect qubit coherence, independent of flux noise. Here, we complement earlier experiments by simultaneous measurements of dephasing and qubit frequency, as well as their correlations, further supported by spectral analysis at mHz frequencies.

In the interacting TLS model, defects may mutually interact electrically or via their response to mechanical strain [20,21]. If the transition energy of a particular TLS is below or close to the thermal level $k_B T$, it undergoes random, thermally activated state switching. We call these two-level fluctuators (TLF) to distinguish them from the more coherent TLS [10] with higher transition energies. Longitudinal coupling between TLS and TLF causes telegraphic fluctuation or spectral diffusion [22] of the TLS' resonance frequencies. The resulting time-dependent frequency fluctuation of near-resonant TLS give rise to phase noise of superconducting resonators [23] and may also cause the parameter fluctuations of qubits [18], investigated here. Figure 1(c) illustrates the physical picture.

We use a nontunable transmon qubit with an Al-AlO_x-Al junction, shunted by coplanar capacitor films of 40 nm TiN, capacitively connected to a microstrip readout resonator. The Hamiltonian describing our qubit is well approximated by $H_q/\hbar = \omega_q a^\dagger a - \alpha (a^\dagger)^2 (a)^2$, where ω_q is the splitting between the ground and excited state, α is the anharmonicity, and $a^\dagger$ and a are the raising and lowering operators. The qubit transition frequency is $\omega_q/2\pi = 4.75$ GHz, and the ratio of Josephson energy to charging energy E_J/E_C is 78, leaving it well protected from charge fluctuations [1,24].

Repeated measurements with an interleaved sequence analogous to Fig. 1(a) reveal time-dependent dynamics of the qubit parameters, an example of which is shown in Fig. 1(b). The Ramsey detuning $\Delta\omega_q$ (blue dots) is a direct measure for the shift in qubit frequency, which fluctuates between multiple discrete values and also shows abrupt qualitative changes in fluctuation dynamics. The relaxation time T_1 (red squares) and Ramsey dephasing time T_2^R (green stars) show fluctuations and a clear correlation with $\Delta\omega_q$, which we will evaluate in the following. A single slice of this measurement [see inset in Fig. 1(b)] required averaging for about 10 s. T_1, T_2^R, and $\Delta\omega_q$ were extracted from fits to single traces. See Supplemental Material [25] for further details on the measurement procedure.

We describe TLS by the generic two-level Hamiltonian $H_{\mathrm{TLS},k} = (\hbar/2)(\epsilon_k \sigma_z + \delta_k \sigma_x)$, where k is the TLS index, ϵ_k is the asymmetry energy, δ_k is the tunneling energy, and σ_i are the Pauli matrices. Assuming the standard form of qubit-TLS coupling [40,41] $H_{\mathrm{int},k} = \hbar g_k \sigma_z (a + a^\dagger)$, transformation into the dispersive frame yields

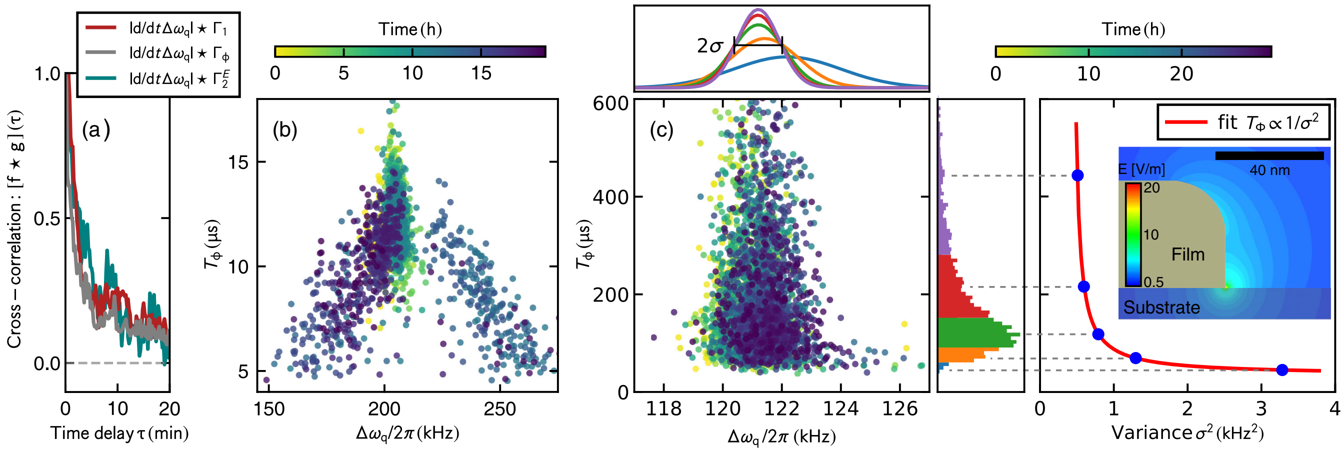

FIG. 2. (a) Cross-correlation of the absolute fluctuation strength and relaxation or dephasing rates of the dataset shown in (b). All curves show significant correlation at zero time delay τ, relating fluctuations in qubit frequency on the order of seconds to relaxation and dephasing. (b),(c) Scatterplots of T_Φ vs Ramsey detuning for two measurements from different cooldowns (identical setup) with drastically different pure dephasing times. The point color indicates the measurement time. In (b) positive, negative, and no correlation occur within the measurement period. In (c) the qubit frequency is relatively stable, bins of pure dephasing times are colored in the vertical histogram, corresponding fits to normal distributions (top panel) are colored accordingly. Lower dephasing times correspond to larger variances in qubit frequency. The standard deviation of the violet curve is indicated exemplarily. On the right, the extracted variances σ^2 are plotted against the corresponding mean values of pure dephasing. A fit to the expected function $T_\Phi \propto 1/\sigma^2$ is in agreement with the data. The simulated field distribution at the superconducting film edge of the qubit capacitance is shown in the inset.

$$H_\mathrm{q} + H_{\mathrm{TLS},k} + H_{\mathrm{int},k} \approx \hbar(\omega_\mathrm{q} + \chi_k \sigma_z) a^\dagger a + \frac{\hbar}{2}(\omega_{\mathrm{TLS},k} + \chi_k)\sigma_z - \hbar\alpha (a^\dagger)^2 (a)^2,$$

where $\chi_k = g_k^2/\Delta$ is the dispersive shift and the detuning between TLS and qubit is given by $\Delta = \omega_{\mathrm{TLS},k} - \omega_\mathrm{q}$.

We can estimate the coupling strength g_k between qubit and TLS from the observed fluctuation amplitude $\Delta\omega_\mathrm{q}$, assuming resonant TLS with a dipole moment on the order of 1 eÅ [42–44] (see Supplemental Material [25] for details). The maximum coupling rate, achieved for TLS located in the junction is approximately 48 MHz. Such strong coupling would allow for much larger changes in qubit frequency than the observed 5–140 kHz. By simulating the electric field distribution we find the coupling strength to TLS at sites closer than 20 nm to capacitor edges is $g_k \gtrsim 100$ kHz, in agreement with our observations. Thus we conclude that the dominant TLS in our experiment reside close to film edges.

To fathom the microscopic origin of the fluctuations, we analyze correlations between all extracted parameters. Ramsey dephasing consists of relaxation and "pure" dephasing T_Φ, connected by $1/T_2^\mathrm{R} = 1/2T_1 + 1/T_\Phi$. In the following, we focus on T_1 and T_Φ or the corresponding rates $\Gamma_1 = 1/T_1$ and $\Gamma_\Phi = 1/T_\Phi$. Scatterplots of two long-term measurements from successive cooldowns with identical setup are shown in Figs. 2(b) and 2(c), where T_Φ is plotted vs $\Delta\omega_\mathrm{q}$. Figure 2(b) exhibited generally larger fluctuations and lower dephasing times; different types of correlation could be observed in the course of a single measurement. A time interval of about 10 hours without obvious correlation between T_Φ and $\Delta\omega_\mathrm{q}$ is followed by alternating positive and negative correlation during times of strong frequency fluctuation. Cross-correlation analysis of this data [Fig. 2(a)] relates the absolute fluctuation strength of $\Delta\omega_\mathrm{q}$ to higher dephasing and relaxation rates, linking slow fluctuations on the order of seconds to dephasing or relaxation up to the order of microseconds. We interpret these observations as coupling to a single spectrally diffusing TLS crossing the qubit frequency several times. To our knowledge, no other interpretation is in agreement with our observations, as will be discussed later. The polarity and strength of the correlations depend on the sign of the detuning between TLS and qubit and their mutual coupling strength.

To perform a quantitative analysis of the connection between the fluctuations in qubit frequency and the pure dephasing time, we examine the variance in qubit frequency associated with multiple ranges of dephasing times [Fig. 2(c)] while the qubit frequency is relatively stable. We bin the frequency shift data according to their associated pure dephasing times, and fit the data in each bin to a Gaussian distribution. Assuming the qubit frequency shifts to be due to random sampling of a linear function (as is the case for small frequency shifts of a dispersively coupled TLS), the standard deviation σ of the distributions will be proportional to the slope of this linear function. Conversely, the pure dephasing rate Γ_Φ in such a situation is proportional to the square of the slope of the frequency change with the random parameter [45]. If the origin of the measured large frequency fluctuations is the same as the one for the pure dephasing, we expect the two slopes to be the same, such that for each bin in pure dephasing time we have $\Gamma_\Phi \propto \sigma^2$, which is in good agreement with our data. For further information on cross correlation, see the Supplemental Material [25].

In repeated measurements and different cooldowns, we find qubit coherence times to be anticorrelated with the maximum amplitude of frequency fluctuations. In our model, this corresponds to different dispersive shifts χ_k due to the respective dominant TLS. During cooldowns with persistently long relaxation and dephasing times as in Fig. 2(c), this shift is low and qubit frequency fluctuations are small. If increased interaction with a TLS leads to shorter relaxation and dephasing times, even for intermediate times without resolvable frequency fluctuations of the qubit, dephasing tends to stay low. This is expected because of the higher frequency noise we cannot resolve by our sub-Hz repetition rate. Possible explanations for abrupt changes in decoherence dynamics are slow thermalization processes in the amorphous parts, logarithmically slow TLS relaxation [46], or background radiation.

Throughout our measurements, reduced coherence manifests itself most strongly in the dephasing times T_Φ and T_2^{R} rather than in T_1 and spin echo T_2^{E}. The observed effective reduction of dephasing by spin echo pulses suggests most of the relevant noise spectrum to lie below the spin-echo cutoff frequency of 25 kHz in our case. This observation is in agreement with the typical maximum fluctuation rate of thermal TLS due to phonons of $\gamma_1^{\max}(T = 20\ \mathrm{mK}) \approx 1.9$ kHz [44] in our case.

To further elucidate the origin of the observed qubit frequency fluctuations, we performed a long term measurement in which we optimized the measurement pulse sequence to gain maximum frequency resolution. If the fluctuations are due to individual TLS, we expect the power spectral density to follow the functional form [40]

$$C(\omega) \propto (1 - \langle\sigma_z\rangle^2)\frac{2\gamma_{1,k}}{\gamma_{1,k}^2 + \omega^2}, \qquad (1)$$

a Lorentz distribution centered at zero frequency. Here, $\gamma_{1,k}$ is the TLS relaxation rate, $\langle\sigma_z\rangle = \tanh(E_k/2k_{\mathrm{B}}T)$ is the thermal equilibrium population of TLS k and $E_k = \sqrt{\epsilon_k^2 + \delta_k^2}$ is its transition energy. Under the assumption of a uniform distribution of TLS barrier heights, the superposition of many such Lorentzian spectra are responsible for the typically observed low-frequency noise of the form $\sim 1/f^\alpha$, usually observed in all solid-state qubits [17].

The PSD of our measurements, shown in Fig. 3, deviates strongly from the ensemble $1/f$ noise limit, but is fit well by a single Lorentzian added to a $1/f^\alpha$-type background.

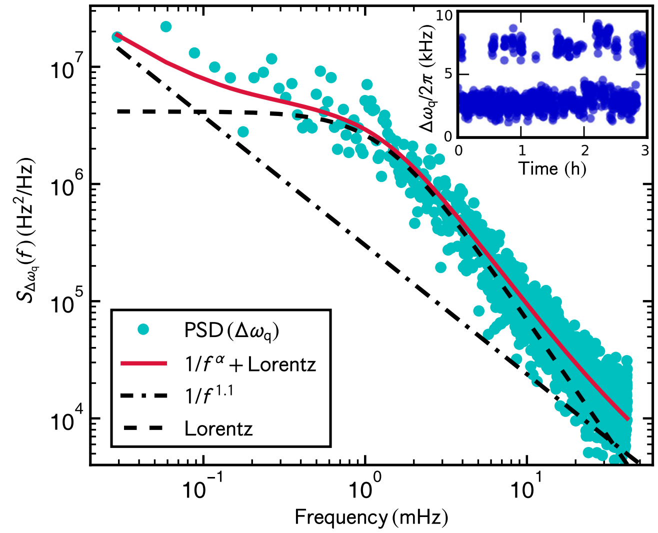

FIG. 3. Power spectral density of frequency fluctuations $\Delta\omega_{\mathrm{q}}$ (cyan dots) in a long-term measurement of 47 h, revealing significant deviation from $1/f^\alpha$ noise (dash-dotted line). A fit (red solid line) is in agreement with the effect of a single thermal TLF (black dashed line) plus $1/f^\alpha$. The inset shows a short section of raw data, showing telegraphic noise that is presumably due to frequency switching of a near-resonant TLS coupled to a single thermal fluctuator. The frequency uncertainty is approximately the size of the dots.

From these measurements, we extract a background parameter of $\alpha \approx 1.1$ and the switching rate of the individual TLS of $\gamma_1 \approx 1$ mHz. For the distribution of switching rates, we estimate a TLF energy of $E_k/k_{\mathrm{B}}T = \ln(\Gamma_\downarrow/\Gamma_\uparrow) = 1.1$ in agreement with the assumption that the switching TLF are located spectrally close to the experimental temperature. For details on the PSD analysis, see Supplemental Material [25].

Finally, we discuss the influence of other possible sources for discrete fluctuations: nonequilibrium quasiparticles (qp), movement of Abriskosov vortices, and temperature fluctuations. The transmon qubit's transition energy is exponentially insensitive to charge fluctuations with respect to $\sqrt{E_J/E_C}$ [1]. In our sample, the change in qubit frequency due to a single qp, switching the charge parity of the capacitance [47,48] is about 2 Hz and thus not observable. A large number of nonequilibrium qp may contribute to relaxation [49] but cannot account for discrete fluctuations in ω_{q} or abrupt changes in dynamics. High magnetic fields may induce field dependent loss in a single junction qubit [50]. To verify the intrinsic insensitivity of this experiment to flux noise, we measured the sample with roughly in-plane magnetic fields up to ± 1 mT, and observed no changes in either coherence or frequency stability. Possible residual fields e.g., due to adsorbates [51] are many orders of magnitude smaller. Significant correlation of the absolute fluctuation strength and the relaxation rate $[|(d/dt)\Delta\omega_{\mathrm{q}}| \star \Gamma_1]$ during periods of low dephasing times require transversal coupling, rendering direct influence of far detuned TLF and critical current fluctuations unlikely. Temperature fluctuations are known to induce low-frequency critical current noise [52]. This effect is exponentially temperature dependent and found to be relevant at $T \gtrsim T_c/3$ in Al-AlO_x-Al junctions. At our experimental temperature of $T = 20$ mK its effect is several orders of magnitude below the observed noise level and can be excluded.

In summary, we used a time-multiplexed protocol in long term measurements to extract correlated coherence information of a nontunable transmon qubit. We find positive and negative correlation between dephasing and fluctuations in qubit frequency on the timescale of seconds to days, which we attribute to the influence of individual dominant TLS, located close to conductor edges. Cross-correlation and PSD analysis confirm this interpretation and ascribe the source of fluctuation to interactions between thermal fluctuators and surface TLS near resonance with the qubit.

Single defects reducing the coherence of qubits by up to one order of magnitude are a major challenge for future quantum computers. Our findings make continuous recalibration a necessity in today's solid-state qubits, although new materials or processing [12,53] might mitigate the problem. However, our results imply that fundamental improvements of qubit parameter stability are necessary in order to realize useful many-qubit systems.

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Note added.—Recently, a paper on comparable observations was published by Burnett *et al.* [54], who independently arrived at the conclusion that TLS are a major contribution to qubit parameter fluctuation.

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