Microscopic charged fluctuators as a limit to the coherence of disordered superconductor devices

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By performing experiments with thin-film resonators of NbSi, we elucidate a decoherence mechanism at work in disordered superconductors. This decoherence is caused by charged Two Level Systems (TLS) which couple to the conduction electrons in the BCS ground state; it does not involve any out-of-equilibrium quasiparticles, vortices, etc. Standard theories of mesoscopic disordered conductors enable making predictions regarding this mechanism, notably that decoherence should increase as the superconductor cross section decreases. Given the omnipresence of charged TLS in solid-state systems, this decoherence mechanism affects, to some degree, all experiments involving disordered superconductors. In particular, we show it easily explains the poor coherence observed in quantum phase slip experiments and may contribute to lowering the quality factors in some disordered superconductor resonators.

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**Introduction.** In highly disordered superconductor films, the kinetic inductance of carriers can exceed the geometrical inductance by orders of magnitude. These materials have been proposed for fabricating new, purely dispersive, high-impedance electronic devices such as tunable (super)inductors [1, 2], slow-wave transmission lines [3], photon detectors [4, 5] and coherent Quantum Phase Slip Junctions (QPSJ) [6], the latter being the dual component of the celebrated Josephson Junction (JJ). The QPSJ proposal has drawn particular interest, as it enables designing new superconducting quantum circuits [7–10] that operate in the previously inaccessible high impedance domain, and which could find applications in quantum technologies. In the recent years, circuits embedding QPSJ of different materials have been tested [11–16], but they all displayed low coherence times compared to those routinely achieved in JJ-based circuits. In the present work, we bring to light a new decoherence mechanism in highly disordered superconductor, due to the charged TLS omnipresent at interfaces and in insulators in solid state systems. This mechanism easily explains the poor coherence observed in QPSJ devices. It also likely contributes to lower-than-expected quality factors reported in resonators made with disordered superconductors [12, 15, 17, 19], even though this mechanism is non-dissipative. This mechanism should affect all the proposals mentioned above, but also experiments probing the Superconductor to Insulator quantum phase Transition (SIT) [20, 21], or the Berezinskii–Kosterlitz–Thouless (BKT) [22–24] phase transition.

Thin-films of various disordered superconductors have been used to implement high kinetic inductance circuits. Provided they are not too close to the SIT (occurring at a normal state sheet resistance $R_{N\Omega}$ of order $h/4e^2 \approx 6.5\, \text{k}\Omega$), these materials can still be qualitatively described by the BCS theory. In this framework, well below the critical temperature, the low-frequency linear response of a diffusive superconductor is described by a kinetic inductance $L_K$ proportional to its normal state resistance $R_N$ [25],

$$L_K = \frac{R_N}{\pi \omega_{\text{gap}}}, \quad (1)$$

where $\omega_{\text{gap}} = \Delta/h$, with $\Delta$ the superconducting gap. With thin films having $R_{N\Omega} \approx 1\, \text{k}\Omega$, and given the common superconducting gaps are in the range $0.2$-$2.0$ meV, one can then achieve sheet kinetic inductance $L_{K\Omega}$ of the order of 1 nH. Thus, these materials should enable highly inductive components that operate up to frequencies of the order of $\omega_{\text{gap}}$ (i.e. tens to hundreds of GHz) which are otherwise unfeasible.

**Experiments.** In this work we have used Nb$_x$Si$_{1-x}$ alloy, with $x = 0.18$, and a film thickness $t = 15$ nm, deposited on an intrinsic Si substrate. The alloy was co-evaporated as described in Ref. [26]. In the normal state, this film has a sheet resistance $R_{N\Omega}$ of about $600\, \text{\Omega}$, weakly dependent on temperature. The RF properties of the NbSi layer were first characterized by fabricating a half-wavelength coplanar waveguide resonator with a 10 µm-wide, 700 µm-long central conductor and measuring it at 17 mK, well below the critical temperature of 0.85 K. From the fundamental resonance (at 6.687 GHz), we extracted the sheet inductance $L_{K\Omega}$ of $0.83$ nH. The measured quality factor $Q_{\text{meas}} = 1.6 \times 10^4$ of the resonance was much lower than the designed external quality factor $Q_{\text{ext}} = 1.6 \times 10^5$, set by the capacitive coupling to the input and output 50Ω lines. Lower-than-expected quality factors have been reported in several resonators made of disordered superconductors [12, 15, 17, 18]; they are usually attributed to unspecified “internal losses”, although dissipative mechanisms are unexpected at these temperatures in BCS superconductors. Finally, the non-linear response to the amplitude of the probe signal gave access to the superconducting coherence length $\xi \approx 40$ nm of the material (see Ref. [27] for details).

Using the above value for $L_{K\Omega}$, we designed lumped-element LC resonators in which the inductors were narrow wires 100-180 nm in width, and the capacitors were rectangular pads at both ends of the inductor (see Fig. 1a). The dimensions were chosen with the aid of numerical simulations in
order to produce well-separated resonance frequencies between 6 and 8 GHz (see Table 1). The resonators were all capacitively coupled to the same input and output 50 Ω transmission lines, weakly enough to all have quality factors larger than $10^4$ in absence of internal losses. The design was transferred into the NbSi layer using e-beam lithography and dry etching in a CF$_4$ – Ar mixture with the negative ma-N resist acting as a mask. After removal of the mask, the sample was wire-bonded on a printed-circuit board and cooled down in a dilution refrigerator. As shown in Fig. 1a, the wiring of the sample incorporated a bias tee and a DC voltage source letting us apply an electric field on the resonators.

![Simplified schematic of the setup](image)

**Figure 1.** (a) Simplified schematic of the setup. Five different NbSi nanoresonators are measured in transmission, using a Vector Network Analyzer. A bias tee and a voltage source $V_g$ enable applying an electric field along the resonators. (b) Simulated (assuming zero internal losses) and measured transmission $S_{21}$ of the sample. The resonance peaks have a Fano resonance shape due to the stray direct coupling of the input and output transmission lines in addition to the coupling through the resonator. The experimental curve is offset vertically to account for the total attenuation and amplification of the setup at 6 GHz. Experimental resonances reach much lower peak transmissions than the simulations, usually indicating that internal losses dominate.

| Resonator | $w$ (nm) | $l$ (µm) | $a$ (m) | $b$ (m) | $f_{des}$ (GHz) | $f_{meas}$ (GHz) | $Q_{ext}$ | $Q_{meas}$ |
|-----------|---------|----------|--------|--------|----------------|----------------|----------|-----------|
| 1         | 100     | 50       | 10     | 10     | 6.44           | 6.21           | 17100    | 1890      |
| 2         | 120     | 50       | 12     | 10     | 6.76           | 6.44           | 20900    | 2280      |
| 3         | 140     | 50       | 14     | 10     | 7.02           | 6.73           | 14000    | 2020      |
| 4         | 160     | 50       | 15     | 10     | 7.35           | 7.00           | 12900    | 2140      |
| 5         | 180     | 50       | 16     | 10     | 7.68           | 7.29           | 16000    | 2650      |

Table I. Design parameters of the five resonators and results of their experimental characterization (see Fig. 1a for resonator dimensions). $f_{des}$ is the designed resonance frequency and $Q_{ext}$ is the designed external quality factor (i.e. simulated total quality factor, with no internal losses). $f_{meas}$ and $Q_{meas}$ are the measured resonance frequency and total quality factor, obtained by fitting $S_{21}$.

In Fig. 1b we show the simulated and measured transmission $S_{21}$ through the five resonators.
The measurements were done at 30 mK, with sufficiently low power for the resonators to be well within their linear response regime. We observe that the resonance frequencies are well-spaced, as designed, with, however, a systematic shift towards lower frequencies which we attribute to a slightly non-nominal fabrication process. We also observe that the measured resonance peaks are markedly lower than the simulated values. Correspondingly, the measured quality factors $Q_{\text{meas}}$, obtained by fitting the $S_{21}$ data as a function of frequency, are much lower than the external quality factors $Q_{\text{ext}}$ predicted by simulations (see Table 1). We further observe that $Q_{\text{meas}}$ is about an order of magnitude lower than what had been determined in the large half-wavelength resonator. Since the small and large resonators were made out of the same NbSi layer and following nominally the same process, the large decrease in $Q_{\text{meas}}$ suggests the quality factor in NbSi resonators depends on the lateral dimension, and is higher in wider structures.

In Fig. 2a we show the variations of the phase of $S_{21}$ at a fixed frequency $f = 6.2086$ GHz, close to the maximum transmission of resonator #1, while the gate voltage is repeatedly swept from 0 to 110 mV over 3.5 s. In each sweep, we observe several abrupt changes in the phase. The gate voltage at which these jumps occur varies from one sweep to another, showing slow drifts and telegraphic signal-like jumps. Furthermore, such measurements repeated at different times displayed long-term variability typical of $1/f$-like noise. Figure 2b shows that the observed flicker noise corresponds to fluctuations in the resonance frequency. Similar features were observed in the other 4 nanoresonators. Due to the frequency fluctuations, the phase of the (electromagnetic) quantum state of the resonator becomes unknown after some time (the dephasing time) and the state can no longer be manipulated deterministically—a phenomenon known as dephasing or decoherence.

**Figure 2.** (a) Variations of the phase of $S_{21}$ at a fixed frequency $f = 6.2086$ GHz, close to the maximum transmission of resonator #1, while the gate voltage is repeatedly swept from 0 to 110 mV over 3.5 s (b) $S_{21}$ in the complex plane for resonator #1. Red dots were obtained by varying the frequency across the resonance. The cloud of black dots corresponds to all the data points in (a). It is aligned along the resonance circle, showing that the jumps observed are really resonance frequency jitter.

**Interpretation.** It is tempting to attribute the fluctuations in the resonance frequency of our nanoresonators to the mechanisms already known to occur in superconducting resonators. Indeed, it was understood in the recent years that microscopic charge systems present in the dielectric material
surrounding superconducting resonators cause frequency jitter and losses in these resonators \cite{28,31}. In this model, the losses are due to TLSs resonantly coupled to the resonator via the AC electric field, each of these TLSs also interacting strongly with other, non-resonant, thermally activated TLSs. Overall, these couplings result in fluctuations of the dielectric constant at the resonant frequency, i.e. fluctuations in the effective capacitance of the resonator. While this TLS-induced dielectric loss mechanism is certainly present in our experiments, one does not expect it to yield observable individual TLS switching events. This is because in our geometry, any TLS occupies an extremely small volume fraction of the resonator mode, and it can only modify the capacitance accordingly. Coupling to spin impurities (magnetic TLSs) may also be a source of fluctuations in superconducting resonators \cite{17,33}, but strong resonant magnetic coupling with individual localized spin impurities is similarly ruled out.

**A new dephasing mechanism.** Here, we propose an alternative explanation for the observed fluctuations. We argue it is the direct interaction of the TLSs with the conduction electrons which causes flicker noise of the kinetic inductance. In the GTM \cite{32}, the corresponding interaction Hamiltonian for a single TLS reads

$$H_{\text{TLS-el}} = \sigma_z \sum_{k k' \eta} V_{k k'} c^\dagger_{k \eta} c_{k' \eta}$$

where $V_{k k'}$ describes the scattering potential, $c^\dagger_{k \eta} (c_{k \eta})$ creates (annihilates) a fermion of wave vector $k$ and spin $\eta$, and $\sigma_z$ is the Pauli matrix describing the TLS. However, in Ref. \cite{32} this term is only considered for its relaxation effect on the TLS, neglecting the corresponding back-action on the conduction electrons. We show below this is legitimate in conventional superconducting resonators in which the kinetic inductance is a negligible part of the total inductance (it happens to be the case for all experiments where TLS losses were carefully analyzed \cite{28,31}), but not in highly disordered superconductors.

For simplicity, we first consider the case where the length $\ell$ of the inductor wire in our resonators is shorter than the electronic coherence length $L_\phi$ in NbSi and use the Landauer-Büttiker framework \cite{34} to describe transport. The normal-state conductance of the wire is given by the Landauer formula,

$$G_N = 2 G_0 \sum_n T_n$$

where $G_0 = e^2/h$, and the $T_n$ are the transmission probabilities of the channels, i.e. the square modulus of the transmission eigenvalues. For disordered materials like our wires, the transmission results from multiple-path interferences though the wire, analogous to a speckle pattern in optics. In other words, the $T_n$ depend in an intricate manner on the specific disorder realization which is unknown. Theory \cite{34} nevertheless provides statistical predictions regarding $G_N$, namely that it has

- an expectation value related to the macroscopic sheet resistance of the material and wire dimensions

$$\langle G_N \rangle = \frac{w}{\ell R_N}$$

- a standard deviation $\sigma_G$ according to Universal Conductance Fluctuations (UCF), i.e. $\sigma_G \sim G_0$ in the “metallic case” ($G_N > G_0$), and slowly decreasing approximately as $\sigma_G \sim G_0 \times$
\[ \sqrt{G_N/G_0} \] in the crossover to the Anderson insulator regime \((G_N < G_0)\) independently of the wire material or dimensions.

When a TLS changes state, it locally modifies the electronic scattering potential in its vicinity, imparting new phaseshifts to the electronic trajectories. For the whole wire, this results in a change of the global electronic speckle pattern, i.e. a modification of the channels, with a change of the conductance \(G_N \rightarrow G_N + \delta G\). If the TLS is located far away from the wire, the change in the potential is vanishingly small and \(\delta G = 0\). In the opposite limit of “strong interaction” where the switching of the TLS radically changes the speckle pattern, \(\delta G\) has a random value with a standard deviation constrained by the UCF. Hence, for any given TLS one expects \(0 \leq |\delta G| \lesssim G_0\) depending on the type of TLS and its distance to the wire. In other words, the random conductance jumps of the individual TLSs follow a distribution, itself derived from the distribution of the coupling strengths (hereafter denoted \(D_{\text{cs}}\)). Another important characteristic of a TLS is its switching time; for the TLS ensemble, switching times are random, following a distribution \(D_{\text{st}}\).

In the superconducting state, \(\delta G\) causes a change of the kinetic inductance of the wire (Eq. (1) with \(R_N = G_N^{-1}\)). This has an effect on the resonance frequency \(f = 1/2\pi\sqrt{(L_K + L_{\text{geom}})C}\) with \(C\) the capacitance of the resonator and \(L_{\text{geom}}\) the geometrical inductance. To first order, a TLS Switching Event (SE) induces a relative change in the resonance frequency

\[
\frac{\delta f}{f} = \frac{\alpha}{2} \frac{\delta L_K}{L_K} = \frac{\alpha}{2} \frac{\delta G}{G_N}, \tag{4}
\]

where \(\alpha = L_K/(L_K + L_{\text{geom}})\) is the participation ratio of \(L_K\) in the total inductance. While \(\alpha \simeq 1\) in our disordered resonator, it is vanishingly small in “conventional” superconducting resonators which are then not dephased by TLS through this mechanism (the dielectric losses of the GTM then being dominant).

Successive single TLS SEs produce a random-walk-like evolution for the conductance (bounded by UCF) and of the resonance frequency. Measured over many SEs, this leads to an increased resonance width \(\Delta f_{\text{FWHM}}\) accompanied with a reduction of the peak transmitted power because the resonator never stays long in optimum transmission condition. Assuming the TLS fluctuations are the main cause of the resonance width \(\Delta f_{\text{FWHM}}\), the corresponding quality factor \(Q_{\text{TLS}} = f/\Delta f_{\text{FWHM}}\) is given by

\[
Q_{\text{TLS}}^{-1} \sim \frac{2\langle \delta f \rangle_{\text{rms}}}{f} = \alpha \frac{\langle \delta G \rangle_{\text{rms}}}{G_N}, \tag{5}
\]

where \(\langle \ldots \rangle_{\text{rms}}\) denotes the rms-averaged quantity over all single TLS jumps during the measurement. \(\langle \delta G \rangle_{\text{rms}}\) can be obtained from the distributions \(D_{\text{cs}}\) and \(D_{\text{st}}\). The UCF upper bound \(\langle \delta G \rangle_{\text{rms}} = \sigma_G \sim G_0\) is reached when the speckle pattern is sufficiently reorganized during the measurement, requiring sufficiently strongly coupled and fast TLSs. From Eqs. (4) and (5), one expects a larger effect of TLSs in systems with a smaller conductance, i.e. a smaller number \(N\) of conduction channels, as \(N \propto G_N \propto w \times t\).

**Microscopic and macroscopic dephasing.** The above discussion brings to light a TLS-Induced Dephasing Mechanism (TLSIDM) in disordered superconductor resonators, i.e. the dephasing of collective, macroscopic, electromagnetic degrees of freedom in the circuit. These results were obtained considering that electrons in the inductors are fully phase-coherent. However, this assumption is unrealistic because our inductors are longer \((\ell = 50\mu\text{m})\) than the largest published values for \(L_{\phi}\) in metals. Moreover, TLS SEs themselves introduce random electronic phase shifts, contributing to shortening \(L_{\phi}\). In the following we take into account such (microscopic) dephasing of individual electrons in our analysis, and work out how it modifies the (macroscopic) TLSIDM.
To this effect, we first examine electronic dephasing only. On average, SEs dephase the electrons after a time $\tau_{\text{TLS}}$ stemming from $D_{\text{cs}}$ and $D_{\text{st}}$ (which already determine $\langle \delta G \rangle_{\text{rms}}$). Assuming TLSs are the main source of electron dephasing, one then has $L_\varphi = \sqrt{D_{\text{TLS}}}$ where $D$ is the diffusion constant. Yet, the value of $L_\varphi$ in the experiment is not known, partly because the standard weak localization determination cannot be performed in the superconducting state. How does this dephasing of individual electronic states affect the collective superconducting state (i.e. the BCS state)? As long as $\tau_{\text{TLS}}$ is large compared to the timescale of the pairing interaction $\hbar/\Delta$ (i.e. $L_\varphi \gg \xi$), the superconducting order adapts to such fluctuations and $|\Delta|$ remains essentially unchanged, just as if the disorder were static (Anderson’s theorem). The phase of the order parameter, however, is a macroscopic electromagnetic degree of freedom which is affected by TLS-induced dephasing proportionally to $\alpha$, as in Eq. \ref{eq:alpha}. In the opposite limit $\tau_{\text{TLS}} < \hbar/\Delta$, fast electron dephasing simply inhibits the formation of the superconducting state. In the crossover, one expects $|\Delta|$ to be reduced and the density of states to be modified, which could be related to anomalous properties reported in some disordered superconductor resonators \cite{36}. In the following, for simplicity, we assume $L_\varphi \gg \xi$.

How does the finite coherence length of electrons modify the TLSIDM? In a quasi-1D incoherent inductor wire (i.e. with $w, t \ll L_\varphi < \ell$), an individual TLS SE modifies the normal state conductance of the wire only over an $L_\varphi$-long segment, yielding a $\delta G$ typically smaller by a factor $(L_\varphi/\ell)^2$ than in the coherent case (i.e. $0 \leq |\delta G| \lesssim (L_\varphi/\ell)^2 G_0$). The resistance changes corresponding to SEs in different segments add in a random walk fashion, so that, averaged over many TLS configurations, $\langle \delta G \rangle_{\text{rms}}$ is smaller than in a coherent wire by a factor $(L_\varphi/\ell)^{3/2}$, just like $\sigma_G$ is reduced in incoherent mesoscopic conductors \cite{34}. Assuming strongly coupled TLSs, one then gets the upper limit for $\langle \delta G \rangle_{\text{rms}}$

$$\langle \delta G \rangle_{\text{rms}} \sim \left( \frac{L_\varphi}{\ell} \right)^{3/2} G_0$$

(recalling however that $L_\varphi$ and $\langle \delta G \rangle_{\text{rms}}$ are not fully independent). Then, using Eqs. \ref{eq:R} and \ref{eq:Q}, this yields the strong-coupling prediction

$$Q_{\text{TLS}}^{-1} \simeq \alpha \left( \frac{L_\varphi}{\ell} \right)^{3/2} \frac{\ell}{w} G_0 R_C$$

setting an absolute lower bound for the quality factor due to TLSIDM.

Comparison with our experiments. The above analysis is in qualitative agreement with our observations. In the first place, the mechanism we propose can explain the observed telegraphic-like frequency jitter, the resulting dephasing and the lower-than-expected quality factors. In the second place, the prediction of larger relative frequency fluctuations in systems with fewer conduction channels explains why the nanoscale resonators appear more lossy than the larger resonator, although they are made of the same material, with (nominally) the same density of volume and surface defects. The data from our 5 nanoresonators is also qualitatively compatible with the proportionality between the quality factor and the nanowire width (Eqs. \ref{eq:Q} & \ref{eq:tau}), but there are too few samples and a too narrow range of widths to regard this as a solid demonstration.

Let us now try to be more quantitative. The largest jumps in Fig. 2 are of the order of $10^6$, which, given the $S_{21}$ resonance circle, corresponds to $\delta f \simeq 0.6$ MHz, and, according to Eq. \ref{eq:G}, a change in the normal state conductance $|\delta G| \simeq 1.4 \times 10^{-5} G_0$. Since we have selected the largest jump observed, we boldly assume it corresponds to a strongly coupled TLS inducing a change of conductance of the order of the disorder-averaged rms value $\sim (L_\varphi/\ell)^2 G_0$, which then yields an estimate of $L_\varphi \sim 0.2 \mu$m. Similarly, if we assume a strongly coupled TLS ensemble, then, matching
the measured quality factor $Q_{\text{meas}} \sim 2 \times 10^3$ with $Q_{\text{TLS}}$ in Eq. (7) yields $L_\phi \sim 0.6 \mu m$, which is of the same order than the above crude estimate. This assumption of strongly coupled TLSs yields a lower bound for $L_\phi$. It could be that there are no strongly coupled TLS in our resonators ($|\delta G| \ll (L_\phi/\ell)^2 G_0$ for all individual TLSs), in which case the observations would be consistent with a larger $L_\phi$.

**TLS types.** We now discuss the type of TLS that cause such decoherence. As NbSi is an amorphous material, TLSs may be atoms jumping between metastable positions in the bulk of the material. However, the observed effect of a DC electric field proves that charged traps or dipolar defects in the vicinity of the wire are at work. It is indeed well known that such charged TLSs are omnipresent in insulators or at interfaces in solid-state electronic devices where, besides the GTM dielectric noise already mentioned [32], they cause charge noise by coupling to surface electronic states (within a Thomas-Fermi screening length $\lambda_{\text{TF}}$). This charge noise is well documented in mesoscopic circuits such as single electron transistors [33, 34], charge qubits [35, 36] or quantum point contacts [37], but also in MOS transistors [38]. The microelectronics industry has shown that a careful choice of materials and process engineering can much reduce the number of charged TLSs, but never completely suppress them. Note that besides the TLSIDM dependence on the number of channels $N \propto w \times t$, for charged TLSs one further expects the TLSIDM to become stronger when the thickness $t$ is reduced to become comparable to $\lambda_{\text{TF}}$, as charged TLSs then interact with a larger fraction of conduction electrons.

**Comparison with other experiments.** The TLSIDM we point out also directly affects QPS experiments in disordered superconductors. The phase slip energy of a uniform quasi-1D nanowire is predicted [39, 40] to scale as

$$E_S = \Delta \frac{G_N}{G_0} \left( \frac{\ell}{\xi} \right)^2 \exp \left( -A \frac{G_N}{G_0} \frac{\ell}{\xi} \right)$$

(8)

where $\Delta$ is the superconducting gap energy, $\xi$ the superconducting coherence length, $\ell$ the nanowire length, and $A$ a numerical factor of order 1. In order to have non vanishing $E_S$, one needs nanowires with a small number of conduction channels. In Ref. [14], it was already noticed that the randomness in disorder realizations induces a relatively large (static) dispersion in values of $G_N$ of order $G_0$, resulting in an irreproducibility of $E_S$ among nominally identical samples. It was also pointed that random offset charges (i.e. essentially frozen charged TLS) were likely contributing to this disorder. Here, we simply extend this reasoning, arguing that charged TLS in the vicinity of the wire also induce dynamical fluctuations in $E_S$. These fluctuations of $E_S$ are dual to fluctuations in the Josephson energy of JJs due to TLS in the tunnel barrier [41], both resulting in decoherence.

We now examine whether the TLSIDM we propose could explain a few published experimental results. In Ref. [15], using the values given for the granular Aluminum resonator shown in Fig. 3a, the measured quality factor would be consistent with $Q_{\text{TLS}}$ of strongly coupled TLSs (Eq. 7) provided $L_\phi \sim 0.5 \mu m$. In Ref. [16], using the values given for the InO$_x$ QPSJs and Eq. (8), one predicts that a conductance noise $\langle \delta G \rangle_{\text{rms}} \sim 1.4 \times 10^{-2} G_0$ due to charge fluctuators would yield a $\langle \delta E_S \rangle_{\text{rms}}/E_S \sim 5\%$ fully explaining the observed Gaussian spectroscopic linewidth. Strongly coupled TLSs (Eq. (6)) would yield such $\langle \delta G \rangle_{\text{rms}}$ figure provided $L_\phi \simeq 15 \mu m$, however, this seems exaggeratedly low for the quoted $\xi = 30 \text{ nm}$. Similar analysis carried out for the NbN QPSJs in Ref. [14], the NbTiN resonators in Ref. [17], or the granular Aluminum resonator #4 in Ref. [18] all lead to similarly low estimates of $L_\phi \sim \xi$. As discussed in the case of our resonator, all these experiments could also (more realistically) correspond to weakly coupled TLS and larger $L_\phi$. Thus, given a suitable ensemble of charged TLS, the mechanism we propose could entirely explain the observed decoherence in all these devices. On the other hand, in some of these devices other mechanisms are clearly contributing to the overall decoherence (in which case the TLSIDM must be
weaker than we have just estimated). For instance, in Ref. 17 spin impurities are shown to play an important role; for the granular Al resonator of Ref. 18, out-of-equilibrium quasiparticles have been identified as a limiting factor 45, and in Ref. 19 the power dependence of the quality factor suggests that TLS dielectric losses of the GTM contribute to the resonance width. Note however that, in the latter Ref. 19, telegraphic fluctuations in the resonance frequency are reported. This is similar to what we observe in our resonators and, for the same reasons, we believe this is a manifestation of the TLSIDM.

Discussion. Let us address or clarify a few points regarding the TLSIDM presented above.

− In resonators, internal energy losses (with an energy decay rate \( \kappa_{\text{int}} > 0 \)) imply a lowering of the quality factor. The reciprocal connection is generally assumed to exist (i.e. lower-than-expected \( Q \Rightarrow \kappa_{\text{int}} > 0 \)), but the TLSIDM is a counter-example disproving it. Indeed, this mechanism operates within the BCS ground state and it is thus strictly non-dissipative (\( \kappa_{\text{int}} = 0 \)). If it were possible to measure fast enough between TLS switching events, one would observe at all times the narrow resonance limited by \( Q_{\text{ext}} \), with the peak frequency jumping randomly. It is only after averaging over many TLS configurations (e.g. due to the measurement bandwidth) that one gets the reduced quality factor (Eq. (5)), mimicking what internal losses would yield. As well, in Fig. 1b, the fact that the measured peak transmission is much lower than in the lossless simulations does not indicate energy being dissipated in the resonator, but power reflected to the input line when the TLSs shift the resonator out of resonance with the probe frequency. Given the jump dynamics involved in the disguise of the dissipationless mechanism as a lossy mechanism, in dubious cases, the relevant mechanism could be diagnosed by measuring with sufficient bandwidth the time-resolved transmitted power at a fixed frequency.

− The TLSIDM does not require any out-of-equilibrium quasiparticles, vortices, etc. which are usually invoked to explain decoherence in superconducting systems. The presence of such features would of course open additional decoherence channels.

− Although the TLSIDM we discuss is lossless, the GTM 32 shows that the TLS ensemble provides a dissipative bath able to absorb the resonator’s microwave photons. This different GTM mechanism does yield internal energy losses (and decoherence) which are not taken into account in the present work, but which may contribute in some experiments. A distinctive feature in the GTM predictions is the non-monotonic dependence of losses on microwave power and temperature, due to the saturation of the resonant TLS. For the TLSIDM, TLSs couple to the wire independently of their energy splitting. Thus, for an ensemble of weakly coupled TLSs (\( |\delta G| \ll (L\varphi/\ell)^2 G_0 \)), we rather expect that the frequency fluctuations (respectively, the quality factor) due to this mechanism should decrease (resp., increase) monotonically when lowering the temperature, because less and less TLSs get thermally excited.

− It is well known that disordered superconductors develop spatial inhomogeneities in \( |\Delta| \) 46 that eventually dominate the properties of the material close to the SIT 17. Since we only consider superconductors sufficiently far away from the SIT, we assume these inhomogeneities remain small and we have not taken them into account (e.g. in Eq. (1)), but accounting for them would not qualitatively modify the TLSIDM we describe.

− Could the effect of charge noise be engineered-out for achieving highly coherent disordered superconductor circuits? After all, in JJ-based qubits this was achieved by operating the Cooper pair box at a “sweet spot” 39 40, or by using the Transmon design 48 49 in which
charge sensitivity is suppressed exponentially. However, in these qubits, charge noise affects the charge degree of freedom in the system Hamiltonian, while in disordered superconductors charge noise modulates a parameter ($L_K$) of the Hamiltonian and, therefore, it cannot be mitigated in a similar way. Short of reducing TLS charge noise itself to an acceptable level, the only way to reduce the effect of TLSIDM is to reduce accordingly the kinetic inductance participation ratio $\alpha$, giving up at the same time the desired high kinetic inductance properties of the circuit. As an alternative, one may wonder if 1D topological superconducting channels, which are impervious to fluctuations in scattering, could form a basis for decoherence-free QPSJs or other high kinetic inductance devices.

**Conclusions.** Because of the omnipresence of charged TLS, the TLSIDM we describe is certainly at work in disordered superconductors devices. We show it can easily explain the disappointing coherence of QPSJ, and that it is likely contributing to the lower-than-expected quality factors of some disordered superconductor resonators. Our results call for more in-depth theoretical and experimental explorations of this TLSIDM, in order to determine the expected distributions $D_{cs}$ and $D_{st}$ for known TLSs, and obtain quantitative predictions for the various noise spectra, coherence times, temperature dependence, etc.

Finally, beyond disordered superconductors devices, we also ponder that fluctuators could have some impact on experiments investigating the SIT [20, 21] or BKT [22, 24] phase transitions in these materials. For instance, it is plausible that the recently reported [50] telegraphic-like reconfigurations in a disordered superconductor are due to the coupling to charged TLS described above. As far as we know, all the theories for these phase transitions assume a static disorder, and one may thus ask if and how the TLS-induced dynamics would modify the characteristics of these transitions. Then, the different densities and types of TLS in various experiments could perhaps explain departures from the expected universality of the SIT [21].

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