Evolution of $1/f$ Flux Noise in Superconducting Qubits with Weak Magnetic Fields

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The microscopic description of $1/f$ magnetic flux noise in superconducting circuits has remained an open question for several decades despite extensive experimental and theoretical investigation. Recent progress in superconducting devices for quantum information has highlighted the need to mitigate sources of qubit decoherence, driving a renewed interest in understanding the underlying noise mechanism(s). Though a consensus has emerged attributing flux noise to surface spins, their identity and interaction mechanisms remain unclear, prompting further study. Here, we apply weak in-plane magnetic fields to a capacitively shunted flux qubit (where the Zeeman splitting of surface spins lies below the device temperature) and study the flux-noise-limited qubit dephasing, revealing previously unexplored trends that may shed light on the dynamics behind the emergent $1/f$ noise. Notably, we observe an enhancement (suppression) of the spin-echo (Ramsey) pure-dephasing time in fields up to $B = 100$ G. With direct noise spectroscopy, we further observe a transition from a $1/f$ to approximately Lorentzian frequency dependence below 10 Hz and a reduction of the noise above 1 MHz with increasing magnetic field. We suggest that these trends are qualitatively consistent with an increase of spin cluster sizes with magnetic field. These results should help to inform a complete microscopic theory of $1/f$ flux noise in superconducting circuits.

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The experimental progress toward building quantum processors with superconducting qubits has advanced significantly in recent years. However, environmental noise and material quality limit qubit coherence, which constrains the ability to scale to larger devices and use different qubit architectures [1–3]. One major limitation to qubit coherence is the ubiquitous low-frequency magnetic-flux noise that displays a $1/f$ power spectral density [4,5]. This noise often limits the dephasing time of frequency-tunable qubits [6–10] and the fidelity of flux-activated gates [11]. Removing the source of $1/f$ flux noise would greatly expand the design space for next-generation quantum hardware, yet the origin of the noise has remained an open question for decades.

Several microscopic theories of magnetic defects in superconducting circuits with emergent $1/f$ flux-noise spectra have been proposed [5,12–15]. However, there is a lack of consensus in the community on both the nature and source of the spins and the spin physics that gives rise to the noise. Nonetheless, several experimental constraints for microscopic flux-noise models have been established, including an emergent $1/f^\alpha$ noise power spectral density from 10^{-4} to 10^8 Hz with $\alpha \lesssim 1$ [16,17], anticorrelation of the noise in loops sharing a boundary [18], perimeter scaling of the noise amplitude [19,20], pivoting of the noise spectrum with temperature about a fixed frequency [21], nonvanishing flux-inductance noise cross-correlation [22], paramagnetic temperature dependence of the spin bath susceptibility [23], and asymmetry of the noise spectrum [16]. Several of these features point to the likely relevance of spin-spin interactions [23,24] and emergent phenomena including spin diffusion [25,26] and clustering [21,22,26–28]. In addition to providing low-frequency dephasing noise, magnetic defects may also play a role in broadband flux noise that contributes to high-frequency energy-relaxation processes [10,16,17], or give rise to other decoherence mechanisms [29,30].

Despite the extensive experimental and theoretical efforts to understand and mitigate $1/f$ flux noise, one critical characterization has remained absent: the response of the flux-noise spectrum to magnetic fields. Such characterization proves experimentally challenging due to the interplay of magnetic fields with superconducting devices (often Al or Nb metallizations on Si or sapphire substrates) and the isolation of flux noise from other noise sources [30–39].

In this Letter, we investigate $1/f$ flux noise as a function of applied magnetic fields up to $B = 100$ G with a superconducting flux qubit, where the field is oriented in the plane of the device. At low frequencies ($\lesssim 10$ Hz), we observe a $1/f$ to approximately Lorentzian transition in the noise spectrum accompanied by an increase of the Ramsey pure-dephasing rate with applied field. Surprisingly, at high frequencies ($\gtrsim 1$ MHz) we observe a suppression of the flux noise and an increase in the $1/f^{\alpha}$ noise exponent α with applied field. These results provide the first study to date of flux-noise-limited qubit dephasing and $1/f$ flux-noise evolution in magnetic fields, which can serve as a new experimental reference for future microscopic theories of flux noise.

We measured capacitively shunted flux qubit samples comprising Al metallizations with Al/AlOx/Al Josephson junctions (JJs) on a Si substrate at the base temperature of a dilution refrigerator with $T \lesssim 40$ mK. The samples were mounted on a cold finger with superconducting magnets in a Helmholtz coil geometry providing an approximately in-plane magnetic field (where we estimate the out-of-plane component to be $\approx 0.2\%$ of the total applied field). The sample was rotated 45° relative to the field direction in order to ensure the qubit was sensitive to spin fluctuations both along and transverse to the direction of the field. The experimental setup and a representative qubit frequency spectrum are shown in Fig. 1 (see Supplemental Material for details [40,41]).

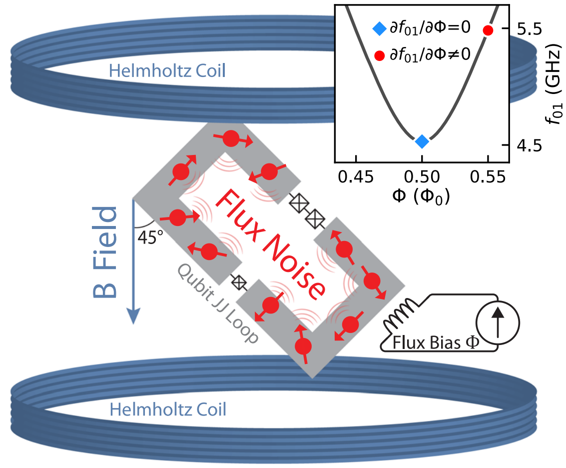

FIG. 1. Flux qubit in a magnetic field. A simplified schematic of the experimental setup. The Josephson-junction (JJ) loop (gray) of a flux qubit is placed in a uniform magnetic field provided by Helmholtz coils (blue). The field is oriented in the plane of the device, and the device is tilted at a 45° in-plane angle relative to the field. Surface spins (red) in proximity to the loop generate flux noise that dephases the qubit. The inset shows an example flux qubit spectrum, with frequency f_{01} as a function of an independent flux bias Φ. The blue diamond indicates the point of first-order flux insensitivity (the so-called "sweet spot"). The red circle highlights an example operating point where the qubit displays flux-noise-limited dephasing.

To probe broad flux-noise trends with applied magnetic field, we first performed standard qubit coherence measurements of the energy-relaxation rate $\Gamma_1 = 1/T_1$ and pure-dephasing rates from Ramsey (Γ_ϕ^R) and spin-echo (Γ_ϕ^E) protocols. We characterized the qubit coherence both at the flux degeneracy point (where the qubit is first-order insensitive to flux noise, i.e., $\partial f_{01}/\partial\Phi = 0$, hereafter referred to as the "sweet spot"), and at a flux bias where dephasing was dominated by flux noise ($|\partial f_{01}/\partial\Phi| = 26.0$ GHz$/\Phi_0$), calibrated at each field with an independent flux control (Fig. 2). In order to extract the pure-dephasing trends, we first isolated the field dependence of Γ_1 [Fig. 2(a)]. We found that Γ_1 varies nonmonotonically, but generally increases with field. These observations may be due to the softening of the Al superconducting gap at higher fields and an associated elevated population of quasiparticles, or the effects of vortices penetrating the thin-film aluminum of our device [31,33,42]. We also observed a slight difference in Γ_1 at the two different working points, which is accounted for in the analysis of the qubit pure dephasing.

We extracted the Ramsey and spin-echo pure-dephasing rates as proxies for the low- and high-frequency flux-noise power. Off the sweet spot, the Ramsey and spin-echo decay envelopes were approximately Gaussian and therefore consistent with $1/f$-limited dephasing [20]. We fit the decays to the product of an exponential envelope from energy relaxation and a Gaussian envelope from pure dephasing, with the relaxation rate fixed from an immediately preceding measurement (see Supplemental Material for details [40]). With increasing field, we observed an increase in the quasistatic noise power probed by Γ_ϕ^R [Fig. 2(b)] accompanied by a decrease in the $\gtrsim 1$ MHz noise probed by Γ_ϕ^E [Fig. 2(c)]. At the sweet spot, Ramsey and spin-echo traces followed exponential decays and were therefore not $1/f$ limited. We observed relaxation-limited spin-echo dephasing ($\Gamma_\phi^E \lesssim \Gamma_1/2$) and Ramsey dephasing of the same order as the relaxation rate ($\Gamma_\phi^R \sim \Gamma_1$). All coherence data were taken in nine separate runs, during each of which the field was first swept from $B = 0$ G to $B = 100$ G and then reversed. No hysteretic behavior was observed in $\Gamma_\phi^{R/E}$.

To gain further insight into the nature of the flux-noise trends, we measured the noise power spectral density (PSD) as a function of magnetic field. For low frequencies ($\lesssim 10$ Hz), we used the single-shot Ramsey technique described in [43], and for high frequencies ($\gtrsim 1$ MHz), we used the spin-locking technique detailed in [44] (see Supplemental Material [40] for additional details). We observed an increase in the low-frequency noise along

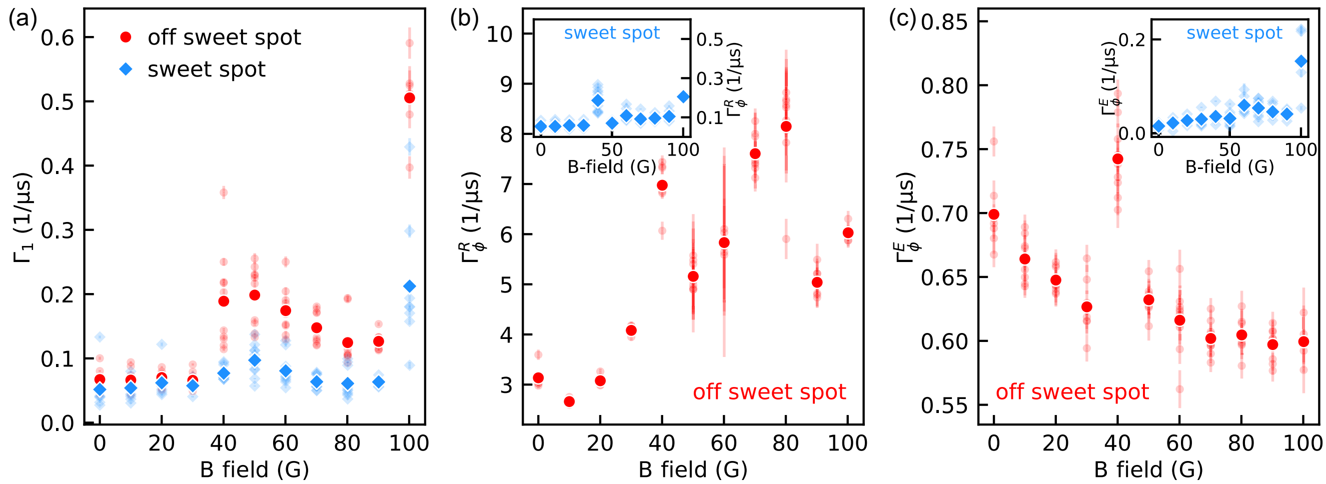

FIG. 2. Evolution of qubit coherence with an in-plane magnetic field. Data taken at the sweet spot ($\partial f_{01}/\partial\Phi = 0$, blue diamonds) and off the sweet spot ($|\partial f_{01}/\partial\Phi| = 26.0\ \mathrm{GHz}/\Phi_0$, red circles). (a) Energy relaxation rate Γ_1. (b) Ramsey pure-dephasing rate Γ_ϕ^R. (c) Spin-echo pure dephasing rate Γ_ϕ^E. Insets in (b),(c) show dephasing rates at the sweet spot. Data was taken during nine field sweeps, with Γ_1, Γ_ϕ^R, and Γ_ϕ^E measured consecutively at each bias point and field. Individual rate measurements are presented as partially transparent small markers with error bars given by the fit uncertainty. Average rates at each field are presented as large opaque markers. The outlier dephasing at $B = 40$ G is likely dominated by noise in the applied field (see Supplemental Material [40] for details).

with a $1/f$ ($B = 0$ G) to approximately Lorentzian ($B \gtrsim 20$ G) transition in the PSD [Fig. 3(a)]. We emphasize that, in contrast to the general noise increase, the noise appears to decrease from $B = 80$ G to $B = 100$ G, which is also present in the Γ_ϕ^R trend. Surprisingly, we also observed beating in Ramsey decays at intermediate fields $50\ \mathrm{G} \lesssim B \lesssim 90$ G (shown in Supplemental Material, Fig. S4 [40]), which may be consistent with telegraphic noise processes giving rise to the corresponding Lorentzian-like spectra; we leave a confirmation of the consistency between these observations to follow-up studies. At high frequencies, we observed a suppression of the flux noise in fields up to $B = 30$ G [Fig. 3(b)] (past this field, high-fidelity calibration for spin-locking spectroscopy became difficult due to the excess low-frequency noise). Both low- and high-frequency PSD trends were reproduced with a second qubit on the same chip. To confirm that flux noise was responsible for the observed trends, we measured qubit frequency noise at the sweet spot and found it primarily magnetic-field-independent and well below the off-sweet-spot noise in the frequency ranges of interest [Figs. S5(a),(c)]. We also observed slight hysteretic behavior of the flux-noise PSD at low frequencies [Fig. S5(b)] but not at high frequencies [Fig. S5(d)]. We note that both noise spectroscopy methods measure the symmetrized PSD of qubit frequency fluctuations, $S_{f_{01}}(f)$, and when operating away from the sweet spot, we used the conversion between frequency- and flux-noise PSDs $S_{f_{01}}(f) = (\partial f_{01}/\partial\Phi)^2 S_\Phi(f)$. To validate this conversion, we confirmed the echo dephasing rate varied linearly with the flux-noise susceptibility $\partial f_{01}/\partial\Phi$ (as in [20]) at multiple magnetic fields.

We now discuss possible physical mechanisms that could explain our observations. We first explore the relevance of spin polarization with the applied field, which depends on temperature and is expected to reduce total superconducting quantum interference device (SQUID) flux-noise power [45]. Similar experiments have observed evidence for the low-frequency ($hf \ll k_B T_{\mathrm{eff}}$) environment of the spin bath being in thermal equilibrium at an effective temperature T_{eff} close to but above that of the mixing-chamber plate [16]. Studies of the native surface spin bath of Al_2O_3 observed signatures consistent with a population of $g = 2$, $S = 1/2$ electron spins [24] at a density matching that of the surface spins producing the ubiquitous $1/f$ flux noise in SQUIDs [23]. We expect saturation of noise suppression from spin freezing to occur in the regime $(\gamma_e/2\pi)B \gg k_B T_{\mathrm{eff}}/h \gtrsim 800$ MHz, where $\gamma_e/2\pi \approx 2.8$ MHz/G is the free-electron gyromagnetic ratio and the lower bound of T_{eff} is set by the measured mixing-chamber plate temperature in our experiment (≈40 mK). Our largest applied field ($B_{\max} = 100$ G) corresponds to a free electron Zeeman energy of $(\gamma_e/2\pi)B_{\max} \approx 280$ MHz, which is below the thermal energy scale of ≈800 MHz. Given the nonmonotonic behavior of the low-frequency flux noise and the saturation of the high-frequency spin-echo dephasing, we suggest that thermal polarization alone cannot explain the observed trends.

One plausible interpretation of the data is an increase in surface spin cluster size with magnetic field, where a cluster refers to a group of interacting spins. In this paragraph, we justify clustering as a relevant phenomenon in superconducting qubit surface spin baths. Clustering is a known behavior of spin ensembles in proximity to a phase transition [46], with the cluster-size distribution depending

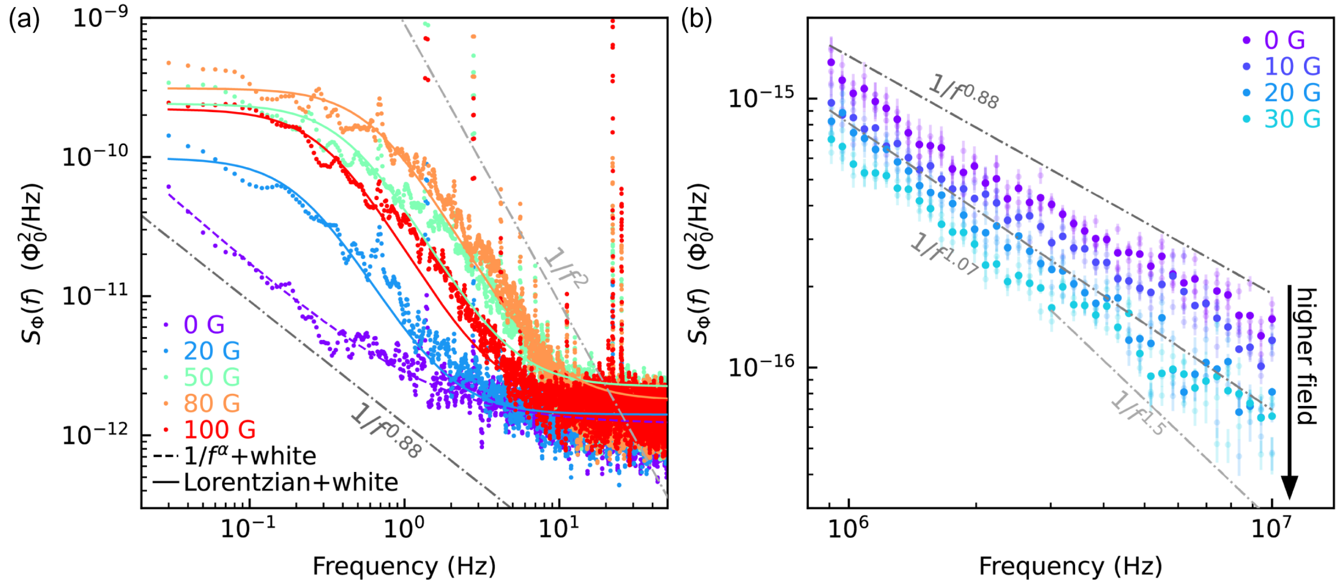

FIG. 3. Evolution of flux noise with an in-plane magnetic field. (a) Low-frequency noise spectroscopy taken with single-shot Ramsey measurements. Data for $B < 100$ G were taken in one upward sweep with $|\partial f_{01}/\partial\Phi| = 22.0\ \mathrm{GHz}/\Phi_0$, and data at $B = 100$ G was taken in a separate upwards sweep with $|\partial f_{01}/\partial\Phi| = 21.0\ \mathrm{GHz}/\Phi_0$. Gray dash-dotted lines serve as guides to the eye displaying power laws $1/f^{0.88}$ (bottom) and $1/f^2$ (top, characteristic of a Lorentzian roll-off). The $B = 0$ G data is fit to a $1/f$ + white noise model (purple, dashed line), and data at each nonzero field is fit to a Lorentzian + white noise model (solid line, color of corresponding data). We attribute the white noise floor to readout infidelity. For further details, see Supplemental Material [40]. (b) Spin-locking noise spectroscopy. Data was taken in four separate field sweeps with $|\partial f_{01}/\partial\Phi| = 30.0\ \mathrm{GHz}/\Phi_0$ for $B \lesssim 10$ G and $|\partial f_{01}/\partial\Phi| = 31.0\ \mathrm{GHz}/\Phi_0$ for $B \gtrsim 20$ G. Individual measurements are presented as partially transparent small markers with error bars given by the spin-locking decay fit uncertainty. Averages at each field are presented with opaque markers. Gray dash-dotted lines serve as guides to the eye displaying the power laws $1/f^\alpha$ with $\alpha = 0.88 \pm 0.02$ (top, α from fit to $B = 0$ G data), $\alpha = 1.07 \pm 0.02$ (middle, from fit to $B = 20$ G data), and $\alpha = 1.5$ (bottom, characteristic of the asymptotic behavior of spin diffusion noise). At higher fields, we note a suppression of the measured flux noise, denoted by an annotated black arrow.

on temperature [46] and field [47]. Multiple experiments on similar superconducting quantum circuits have observed evidence of native surface spin baths being near a magnetic phase transition while at standard operating conditions (i.e., millikelvin temperatures and nominally zero applied field) [23,26]. Increasing cluster size has been previously hypothesized as a source of the spectral pivoting of $1/f$ noise with decreasing temperature [21]. We note that experimental and theoretical studies have suggested that high-frequency $1/f$ flux noise emerges from spin diffusion dynamics [25,26,46,48], while a distinct mechanism is responsible for the low-frequency flux noise, such as longer-time fluctuations of the net magnetization of clusters [26,46].

We now discuss the low-frequency ($\lesssim$10 Hz) flux noise spectrum [Fig. 3(a)]. It has been suggested that clusters of spins may act as "macrospins" with effective magnetic moments and relaxation processes, which produce an ensemble of telegraphic noise processes giving rise to $1/f$ noise [27,28,46]. Assuming the effective relaxation rate of a cluster rapidly decreases with the number of spins in the cluster [46], an increasing size with applied field would be consistent with the rise in low-frequency flux noise. The transition from $1/f$ to approximately Lorentzian noise suggests a narrowing of the distribution of cluster relaxation rates, which may reflect clusters becoming more homogeneous in size with applied field as a result of, e.g., fewer total clusters or size saturation due to the finite dimension of the superconducting wire. We note that the Lorentzian cutoff frequency does not saturate with magnetic field, but appears highest at $B \approx 80$ G. This nonmonotonic behavior may be due to the field dependence of system parameters such as individual spin relaxation times, the effective spin diffusion constant, cluster sizes, etc.

We now proceed to the high-frequency ($\gtrsim$1 MHz) flux-noise spectrum [Fig. 3(b)]. We present two potential mechanisms for the suppression of spin diffusion that would lead to the lowering of flux noise in the MHz range: (1) spin clustering, and (2) inhomogeneous broadening of the spin bath. The growth of spin clusters (and corresponding reduction of their flip rate [46]) would reduce the number of smaller clusters contributing to high-frequency noise [21]. Beyond this generic trend, we consider the case of ferromagnetic or random clusters. In the case of ferromagnetic clusters, growth would inhibit flip-flop processes contributing to spin diffusion by decreasing the number of participating antiparallel spin pairs. In the case of random clusters (in which spins are oriented randomly), growth would inhibit diffusion processes past a critical timescale $f_c^{-1} \propto L^2/D$, where D is the effective spin diffusion coefficient and L is the spatial extent of a cluster that determines how far excitations can freely diffuse before running into a boundary—at frequencies above f_c, the noise PSD asymptotically approaches $S(f > f_c) \sim 1/f^{1.5}$ [25,26]. In addition to a reduction of the noise level, our data display an increasing noise exponent α with applied field that is consistent with an increase in L. We note that in an earlier cooldown we observed $\alpha \approx 1.5$ at magnetic fields $B \gtrsim 12$ G in multiple datasets, although this behavior was not observed during the subsequent cooldown. We also note the apparent saturation of Γ_ϕ^E, which may suggest a saturation of spin cluster sizes complementing the $1/f$ to Lorentzian transition in the low-frequency noise.

Another possible mechanism for the suppression of spin diffusion (i.e., spin flip-flops) is inhomogeneous broadening of the spin bath from local variations in the applied field [49,50], which would reduce the effective diffusion constant D [51]. Spin flip-flops are possible between resonant spins (detuned less than their interaction strength) with antiparallel orientations. Since the saturation of Γ_ϕ^E occurs at lower field than would be expected from polarization (reorientation) of the surface spins, we suggest that inhomogeneous broadening provides a more consistent explanation for both the qubit coherence and noise spectroscopy data. A number of mechanisms may lead to inhomogeneous broadening such as spatially inhomogeneous Meissner screening, or a statistical distribution of the effective gyromagnetic ratios of magnetic defects. Attributing the saturation of Γ_ϕ^E entirely to such broadening, we place a rough bound on the spin-spin interaction strength assuming the spin energy is given approximately by the applied field Zeeman splitting—a spin experiencing the bare field would have a frequency $\approx(\gamma_e/2\pi)B$, and a nearby spin experiencing no applied field (i.e., on an adjacent face of the wire that is entirely shielded) would have a frequency ≈ 0. Flip-flop processes would be inhibited between these spins if their coupling strength J satisfies $J < h(\gamma_e/2\pi)(B - 0)$. With a saturation field $B_{\text{sat}} \approx 50$ G, we have $J/h \lesssim 150$ MHz.

In summary, our results provide the first characterization of flux-noise-limited dephasing in superconducting qubits as a function of applied magnetic field. Our data reveals a distinct $1/f$ to approximately Lorentzian transition of the noise spectrum below 10 Hz as well as a suppression of noise above 1 MHz. The observed trends are consistent with increasing spin cluster sizes with applied field, although more experimental and theoretical investigation is required to validate this interpretation. Further insight can be obtained by mapping the flux-noise response at higher fields using magnetic-field-resilient devices (e.g., niobium or thinner aluminum metallizations), or by probing the noise response to applied fields while varying device materials or field angle. In addition, searching for resonant peaks in the flux noise spectra at higher frequency ($\gtrsim$10 MHz) as a function of magnetic field may provide valuable clues about the electronic and chemical configuration of the magnetic defects comprising the spin bath. Such signatures of coherent fluctuators in flux-noise spectra have already been observed, albeit at nominally zero field, and without consistent reproducibility [44]. Already, we anticipate that our results can provide a new experimental constraint for future flux-noise models incorporating magnetic-field dependence [52], which may bring us one step closer to solving the decades-long open question of the microscopic origin of $1/f$ flux noise in superconducting circuits.

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