Correlated charge noise and relaxation errors in superconducting qubits

The central challenge in building a quantum computer is error correction. Unlike classical bits, which are susceptible to only one type of error, quantum bits (qubits) are susceptible to two types of error, corresponding to flips of the qubit state about the X and Z directions. Although the Heisenberg uncertainty principle precludes simultaneous monitoring of X- and Z-flips on a single qubit, it is possible to encode quantum information in large arrays of entangled qubits that enable accurate monitoring of all errors in the system, provided that the error rate is low. Another crucial requirement is that errors cannot be correlated. Here we characterize a superconducting multiqubit circuit and find that charge noise in the chip is highly correlated on a length scale over 600 micrometres; moreover, discrete charge jumps are accompanied by a strong transient reduction of qubit energy relaxation time across the millimetre-scale chip. The resulting correlated errors are explained in terms of the charging event and phonon-mediated quasiparticle generation associated with absorption of γ-rays and cosmic-ray muons in the qubit substrate. Robust quantum error correction will require the development of mitigation strategies to protect multiqubit arrays from correlated errors due to particle impacts.

The two-dimensional surface code is widely seen as a promising approach to realization of a fault-tolerant quantum computer based on superconducting integrated circuits. In this architecture, quantum information is encoded in a two-dimensional fabric of superconducting qubits with nearest-neighbour connectivity. Provided that gate operations and measurements are performed above a certain fault-tolerant threshold, it is possible to uniquely identify and correct errors in the system by monitoring multiqubit parity operators of the form \(XXX\) and \(ZZZZ\), where \(X\) and \(Z\) are single-qubit Pauli operators. In recent years, a number of groups have achieved beyond-threshold fidelities for single- and two-qubit gate operations \(^{1,2}\) and for qubit measurement \(^{3,4}\), and steady improvements in performance are expected. The rigorous proof that it is possible, in principle, to achieve fault tolerance once threshold levels of fidelity are reached underpins much of the optimism for the surface code. However, this proof rests on the assumption that errors across the multiqubit array are uncorrelated in both space and time. Although it is possible to mitigate errors that are weakly correlated across neighbouring qubits (L.F. & L.B.I., manuscript in preparation), quantum error correction will break down in the face of simultaneous errors that are correlated over large length scales.

Here we demonstrate spatially correlated charge fluctuations in a superconducting multiqubit chip over length scales of hundreds of micrometres, accompanied by correlated relaxation errors that extend over several millimetres. The data are compatible with absorption in the qubit substrate of cosmic-ray muons and γ-rays from background radioactivity. We perform detailed numerical modelling to determine the spatial profile of the charge burst associated with an absorption event; in addition, we present a simple model that describes the propagation of energy released by the event through scattering of pair-breaking phonons. These results have far-reaching implications for proposed error correction schemes such as the surface code that requires simultaneous monitoring of all errors in the system, provided that the error rate is low. Another crucial requirement is that errors cannot be correlated. Here we characterize a superconducting multiqubit circuit and find that charge noise in the chip is highly correlated on a length scale over 600 micrometres; moreover, discrete charge jumps are accompanied by a strong transient reduction of qubit energy relaxation time across the millimetre-scale chip. The resulting correlated errors are explained in terms of the charging event and phonon-mediated quasiparticle generation associated with absorption of γ-rays and cosmic-ray muons in the qubit substrate. Robust quantum error correction will require the development of mitigation strategies to protect multiqubit arrays from correlated errors due to particle impacts.

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of the chip with separation of order 3 mm, the rate of simultaneous charge jumps is consistent with random coincidence.

As mentioned above, the characteristic length \( r_{\text{corr}} \) sets the scale over which charge is sensed in the bulk substrate. The high degree of correlation in charge fluctuations sensed by qubits with 640 μm separation indicates charging events with a large spatial footprint. There are two obvious candidates for such events: absorption of cosmic-ray muons in the qubit substrate and absorption of γ-rays from background radioactivity. These events deposit energy of order 100 keV in the qubit substrate, roughly 10 orders of magnitude greater than the ~10 μeV energy scale of the qubit states. In both cases, the absorption event liberates charge in the substrate; a considerable fraction of the free charge diffuses over hundreds of micrometres, leading to a large spatial footprint for the charging event that can be sensed by multiple qubits.

We perform detailed numerical modelling of charge bursts induced by the absorption of cosmic rays and background radioactivity. We use the GEANT4 toolkit to calculate the energy deposited in the Si substrate; in Fig. 3a, we display a subset of the simulated particle tracks in the qubit chip. A simplified model of the cryostat (including vacuum can, radiation shields and stage plates) is used to calculate the flux of muons and γ-rays at the chip (see Supplementary Information). The angular and energy distribution of simulated muons reproduces measurements of cosmic-ray muons at sea level, and the photons from background radioactivity are generated isotropically according to the measured energy distribution of γ-rays from environmental radioactivity (see Supplementary Information Fig. 9). Each energy deposit liberates one electron–hole pair per 3.6 eV of energy transferred to the substrate. The subsequent diffusion of charge is modelled using G4CMP. This charge transport simulation takes into account anisotropy in the electron band structure, which leads to a separation of the positive and negative charge liberated by the burst event, as demonstrated in ref. 16. In Figs. 3b, c, we display the electron and hole distributions used in the simulation. The characteristic trapping length \( \lambda_{\text{trap}} \) is tuned to match the experimentally measured charge histograms (see Supplementary Information for details). We find for \( \lambda_{\text{trap}} = 300 \) μm and \( f_c = 0.2 \) that the simulated single- and two-qubit charge histograms are in good qualitative agreement with the measured histograms and provide a reasonable quantitative match with the correlation probabilities and charge asymmetries extracted from the data. The trapping length \( \lambda_{\text{trap}} \) is a critical materials parameter that determines the electrostatic coupling of particle impact events to nearby qubits. Based on our analysis, we infer a rate of γ-impacts on the 6.25 × 6.25 mm² chip of 19.8(5) mHz; the contribution of cosmic-ray muons to the measured rate of charge bursts is around 40 times smaller (see Supplementary Information). A separate measurement of environmental radioactivity in the laboratory using a NaI scintillation counter yields an inferred rate of γ-impacts on the qubit chip of 9 mHz. The factor of 2 discrepancy could indicate a local source of radioactive contamination within the cryostat.

Ultimately, the energy released by particle absorption will be transferred to the phonon reservoir in the qubit substrate. Phonons will rapidly scatter to the gap edge of the Nb groundplane by breaking Cooper pairs; non-equilibrium quasiparticles in the vicinity of the Al junction leads are expected to become trapped and suppress qubit relaxation time \( T_1 \) (refs. 17–22). In a separate series of experiments, we use one qubit as a trigger for charge bursts while additional qubits are used as local probes of \( T_1 \). Figure 4a shows the pulse sequence for the experiment. On qubit 1 (Q1) we perform the same charge Ramsey sequence as in Fig. 2, whereas on qubits 2 and 4 (Q2, Q4) we perform a stripped-down inversion recovery experiment consisting of a premeasurement to initialize the qubit, an X-gate, a fixed idle time of 10 μs and a second measurement. The sequence is repeated continuously with a cycle time of 40 μs.
We identify burst events when there is a large discrete change in the running average of the Ramsey amplitude measured on Q1, allowing us to align and average traces from the probe qubits. In the absence of burst events, the inversion recovery sequence yields average occupations of the qubit |1⟩ state that are consistent with the separately measured qubit T1 times. When a charge burst is detected in Q1, however, we find a clear suppression in the |1⟩ occupation of Q2 and Q4. Fitting this dropout with an exponential recovery convolved with a Gaussian to account for timing.
Fig. 3 | Modelling of muon and γ-ray impacts. a, Top and side views of muon (blue, 30 events) and γ-ray (red, 60 events) tracks for a collection of simulated impact events in the 6.25 × 6.25 mm² chip. For a single muon track, a sample distribution of generated electrons (green) and holes (orange) is shown. Qubit locations are indicated by filled black circles. The crystal orientation of the Si substrate is ⟨001⟩; the crystal ⟨110⟩ direction is as indicated. The chip is oriented within the cryostat as indicated (orientation is relevant for the simulation of cosmic-ray muons, which predominantly arrive from the vertical direction). b, c, Electron (b) and hole (c) distributions (arb. units) used to simulate induced offset charge. Electrons tend to travel along the crystal valleys, whereas the distribution of holes is spherically symmetric.

We briefly discuss the implications of these results for the realization of fault-tolerant superconducting qubit arrays in the surface code; for a detailed discussion, see Supplementary Information. We define correlation degree m as the number of qubits in a line to which an error couples. It can be shown that the fault-tolerant threshold p_m for correlated errors of degree m is given by p_m = p^m, where p is the fault-tolerant threshold for uncorrelated errors (L.F. and L.B.I, manuscript in preparation). The relaxation (bit-flip) errors associated with phonon-mediated quasiparticle generation are particularly damaging, as they couple to all qubits in a millimetre-scale chip. We identify two additional correlated error mechanisms: correlated phase-flip errors due to exponentially small (but non-zero) frequency shifts induced by correlated charge noise, and correlated bit-flip errors induced by the sudden charge transient associated with particle impact. Even for a nominally charge-insensitive qubit such as the transmon with $E_J/h = 250$ MHz and $E_J/E_C = 50$, we find

uncertainty in the trigger, we find a recovery timescale of 130 ± 40 μs. We conclude that the same process that gives rise to discrete jumps in offset charge also leads to correlated suppression of qubit T_1 time over length scales in excess of 3 mm. In general, quasiparticles that become trapped in the junction leads in the immediate aftermath of a particle impact event will induce both upward and downward qubit transitions^23 that will be correlated across the qubit array.

The timescale for recovery following a particle impact can be understood in the following way. Phonons propagate diffusively to the boundary of the chip in a time $x_0^2/c_z z_0$, where $x_0 = 6.25$ mm is the lateral dimension of the chip, $c_z = 6 \times 10^3$ m s⁻¹ is the sound speed in the Si substrate and $z_0 = 375$ μm is the chip thickness. The chip is thermally anchored at four corners, with a fraction $\beta = 0.2$ of the chip perimeter acoustically coupled to the chip enclosure. We therefore find a characteristic dwell time for athermal phonons in the substrate of order $x_0^2/c_z z_0 = 100$ μs, in qualitative agreement with the measured recovery time.
that the rate of correlated phase-flip errors is considerable, with 0.9% (3.8%) of γ-ray (muon) impacts giving rise to correlated phase-flip errors above the $10^{-4}$ level in qubit pairs separated by 640 µm, and with 7.2% of muon impacts giving rise to correlated phase-flip errors above the $10^{-3}$ level in qubit pairs separated by 3 mm. In general, the exponential sensitivity of the qubit array to correlated errors represents a serious design constraint: for a given error mechanism with fixed spatial footprint, the need to protect against correlated errors will dictate how closely spaced the qubits can be.

A clear understanding of the underlying physics of particle impact events in the qubit substrate will allow the development of mitigation strategies to suppress or even eliminate correlated errors. We discuss several possible approaches below.

First, one can operate the quantum processor in a clean environment that provides shielding against cosmic-ray muons and background γ-rays. Such measures are routinely taken in ultrasensitive searches for rare events, such as neutrinoless double beta decay24,25 or dark matter interactions26,27. Underground sites enable the reduction of cosmic-ray γ-ray flux to negligible levels28–30. Similarly, the cryostat can be shielded in massive lead and copper structures to absorb γ-rays. A few centimetres of lead shielding guarantees a suppression of the γ-flux by $10^2$ orders of magnitude. Finally, the materials used to construct the device and its enclosure can be selected to be radio-pure and processed through electrochemical treatments that remove surface contamination28,31.

Second, one could reduce the sensitivity of the qubit to the burst events. Reduction of the size of the qubit island and reduction of the gap from the island to ground will limit the sensitivity of the qubit to electric fields in the substrate. It is important to note that the near-continuous groundplane in the geometry studied here provides excellent electrostatic screening against charge in the bulk. We anticipate that a multiqubit architecture that lacks a groundplane will be much more susceptible to correlated phase-flip errors induced by charge bursts. To combat quasiparticle-induced $T_e$ suppression, mitigation strategies could be adopted to prevent the direct diffusion of quasiparticles, for example involving superconducting bandgap engineering31 or normal-metal quasiparticle traps32. Finally, steps could be taken to promote the relaxation of high-energy phonons below the gap edge and to enhance the rate of removal of phonons from the qubit substrate33,34. modest improvements in the acoustic anchoring of the substrate could accelerate recovery of the chip following particle absorption, minimizing correlated relaxation errors due to quasiparticles.

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Data availability
The data shown in this paper are available upon request.

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