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Final Scientific/Technical Report

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Name of recipient: Massachusetts Institute of Technology

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Measurement of Correlated Qubit Errors in the Presence of a Cs-137 Gamma Radiation Source - MIT

1. Abstract

Previous experiments at MIT have shown that ionizing radiation reduces the average coherence of superconducting qubit coherence [1]. Recently, others have observed spatiotemporally correlated errors in superconducting qubit arrays and suggested ionizing radiation as the source of these error events [2–4]. The spatiotemporally correlated errors observed in superconducting qubit arrays have been speculated to originate from ionizing radiation, but it has not been shown that ionizing radiation is the source of these events. During the past year of our research under program DE-SC0021181 we demonstrated that ionizing radiation is a source of spatiotemporally correlated qubit relaxation events.

2. Summary of project activities

2-1. Original hypotheses

The spatiotemporally correlated qubit relaxation events observed in transmon qubit arrays are expected to result from ionizing radiation impacts. We hypothesize that the presence of a manufactured gamma radiation source, e.g. Cs-137, will result a higher occurrence of multi-qubit relaxation events.

2-2. Approaches used

We measured an array of 10 fixed-frequency transmon qubits (Fig. 1a). Detection of spatiotemporally correlated error events required sampling of transient (~ 1 ms) changes of each qubit's energy-decay rate. An instance of qubit relaxation was recorded whenever a qubit was found in its ground state after excited state preparation, implemented by a pulse sequence for qubit control and state readout. For each measurement cycle, the states of all qubits were simultaneously measured following preparation (π-pulse) and a fixed 1 μs delay. We observed instances of relaxation if a qubit's inverse decay rate was comparable to the delay duration ($1/\Gamma 1 = T1 < 1$ μs).

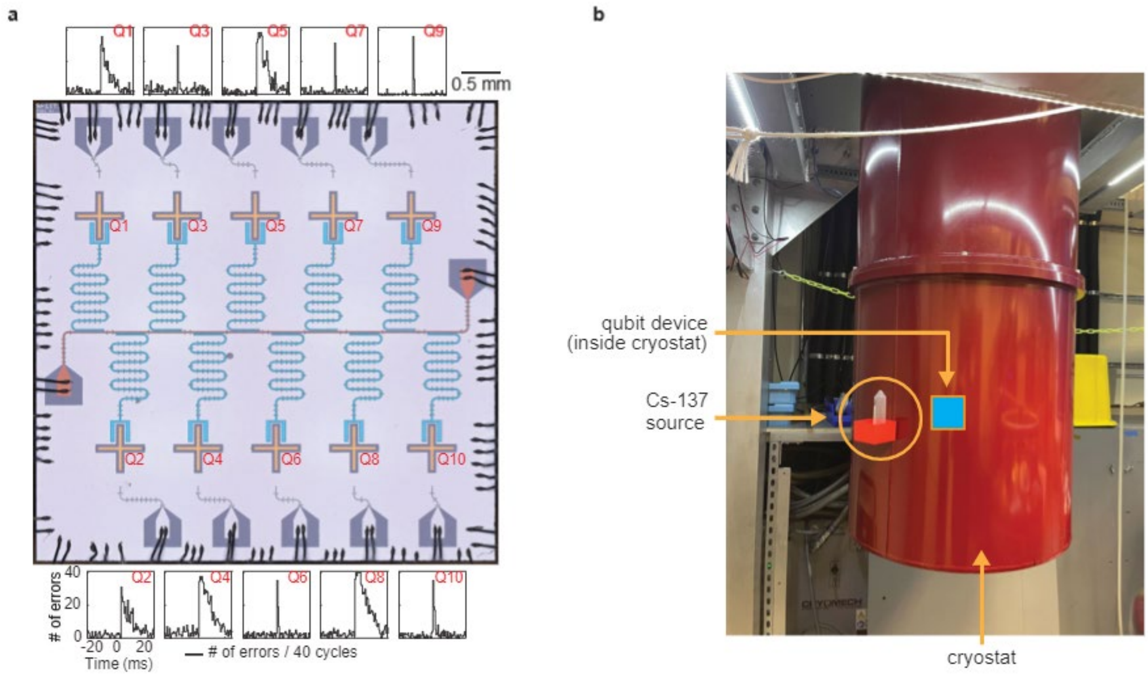

*Figure 1: **Device layout, an example spatiotemporally correlated error event, and experiment setup.** (a) An optical micrograph of the 10-transmon qubit device under test. Individual qubit responses during a spatiotemporally correlated qubit relaxation event is shown in panels above and below the chip image, which are all plotted with the same axes scales. (b) The experiment cryostat containing the qubit device. A Cs-137 gamma ray source was placed next the cryostat, approximately 20 cm from the qubit device.*

2-3. Findings

We monitored qubit relaxation rates for 20 s durations (106 measurement cycles). After data collection, we detected event of spatiotemporally correlated qubit relaxation (an example event is shown in Figure 1a). Since spatiotemporally correlated relaxation events are characterized by a sudden increase and long recovery of qubit relaxation rates, we searched for these events by evaluating a cross-correlation time-series between qubit relaxation data (summed over all qubits for each cycle) and an expected temporal evolution for qubit relaxation rates during an event. The expected temporal correlation of total qubit relaxation was defined as a one-sided exponential with a 2 ms recovery time- constant. The onset of spatiotemporally correlated relaxation events were identified within each data collection period as a transient peak in this cross-correlation above a threshold value. An example of an event is shown in Figure 1b, which depicts a simultaneous increase of relaxation for all qubits throughout the device.

We tested if ionizing radiation has an effect on the occurrence rate of spatiotemporally correlated qubit relaxation events by repeatably exposing the qubit device to gamma ray radiation from a Cs-137 source (17 µCi activity) placed outside the experiment cryostat (Fig. 1b). The Cs-137 source emits 0.7 MeV gamma rays, some which are expected to scatter through the cryostat shielding before depositing O(100 keV) energy into the qubit device. We performed trials during which we measured the number of detected spatiotemporally correlated events (per 400 s) with the Cs-137 present (as shown) and with the Cs-137 removed (stored in a lead container). Each trial was repeated a total of 10 times. Figure 2 shows the number of observed events (per 400 s) versus trial index. These data show the occurrence rate of spatiotemporally correlated events is increased when the Cs-137 source is present. Our measured supports the claim that spatiotemporally correlated qubit relaxation events can result from ionizing radiation impacts.

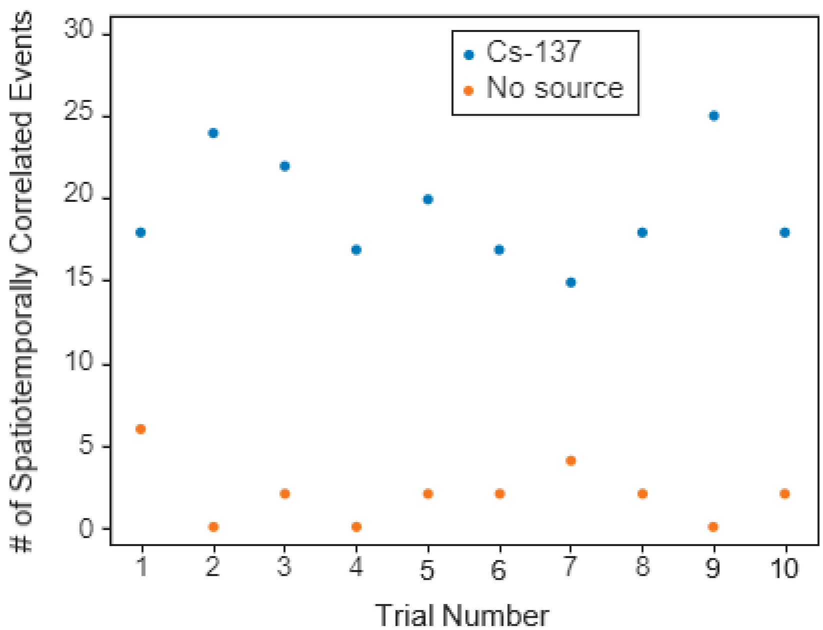

Figure 2: Experiment results The number of spatiotemporally correlated qubit relaxation events versus trial index, for which each trials consists of events monitoring for 400 s without a source present followed by monitoring for 400 s with a source present.

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Dilution Refrigerator Shielding - PNNL

3. Abstract

Naturally occurring ionizing radiation has been shown to create an excess of quasiparticles that limits the performance of superconducting qubits [1-3]. Prior work by this MIT-PNNL collaboration made the initial definitive observation [1] leading to a subtopic of QIS-nuclear-physics collaboration that explores the effects of radiation on superconducting qubits. The present award supported the establishment of a low-background facility at PNNL to serve research in that subtopic by us and our collaborators, with support from NP and other agencies.

4. Summary of project activities

2-4. Original hypotheses

With knowledge that radiation reduces the performance of superconducting devices, it follows that their performance can be improved in low radiation environments. The ideal environment for R&D towards radiation-tolerant devices has reduced backgrounds from a combination of shielding and underground location. Furthermore, if inevitable radiation events can be independently detected, then associated qubit errors can be tagged, even if not corrected, allowing for the vetoing of erroneous qubit operations [4]. Such sensor-assisted fault mitigation should improve the performance of quantum algorithms.

2-5. Approaches used

The first hypothesis, that superconducting device performance can be improved in a low-background environment, was addressed by establishing such an environment. Figure 1 shows the design of a dilution refrigerator shield supported by this award.

PNNL acquired a Bluefors LD400 dilution refrigerator and installed it in a shallow underground laboratory [5] using internal funds. The refrigerator is currently operational, supporting experiments on several projects funded by both NP and other sponsors. The shield design is complete, and the frame has been constructed. Assembly of the lead walls will be competed in the future with support from Ben Loer's Early Career Research Program Award (ECA). The roof and back wall of the shield are permanently fixed in place and the back wall is in turn securely mounted to the concrete wall of the laboratory. The frame is designed such that the walls and roof will not collapse in a seismic event. The shield is shown in its open position as it would be during installation of experiments into the refrigerator. The three non-fixed walls and the floor move on rails to completely enclose the refrigerator during operations.

The radiation environment at the site of the refrigerator was measured and used to model the radiation dose to devices inside the refrigerator. Qubit devices themselves were assayed by inductively couled plasma mass spectrometry (ICPMS). Radiation doses from other sources were then evaluated. It was anticipated that the primary dose in this facility would be from materials in the refrigerator, and especially materials close to the qubit such as the carrier boards on which qubits are mounted. Common qubit carrier board materials (Iinterposers") were assayed (funded by Loer's ECA). A mature draft of a paper about the radiation environment, coauthored with

MIT collaborators is in hand and will be submitted for publication soon. Its preliminary results are summarized in the Findings section and Table 1 below.

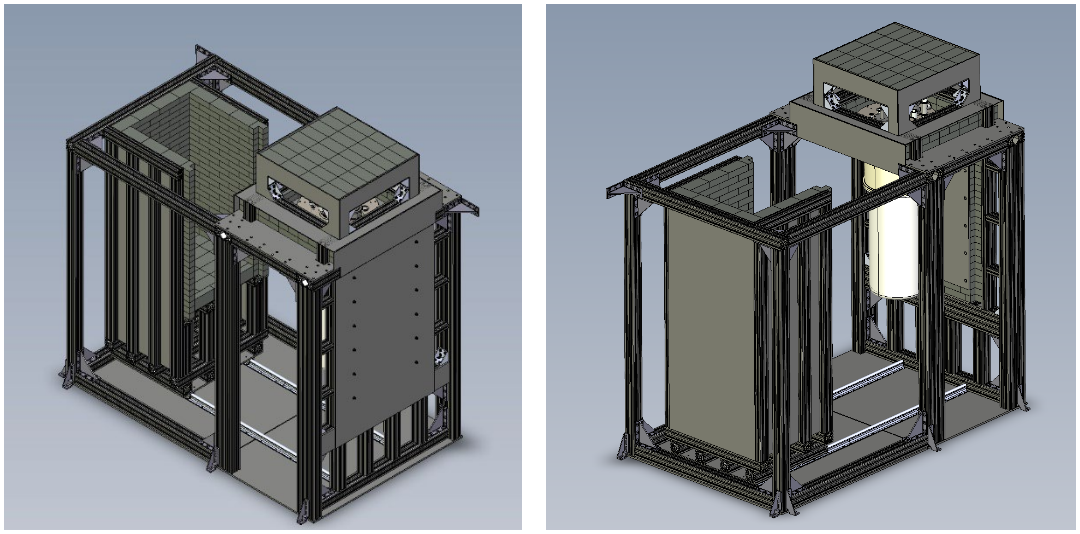

Figure 1: Alternate views of the shield in its open position. In operation, the four-sided assembly moves to completely enclose the refrigerator (white).

The second hypothesis, that sensor assisted fault mitigation could improve the performance of common algorithms like variational quantum eigensolvers, was pursued by running experiments on IBM's quantum hardware. Figure 2 shows our simple circuit for detecting correlated bursts of errors, similar to those seen on Google devices by [3].

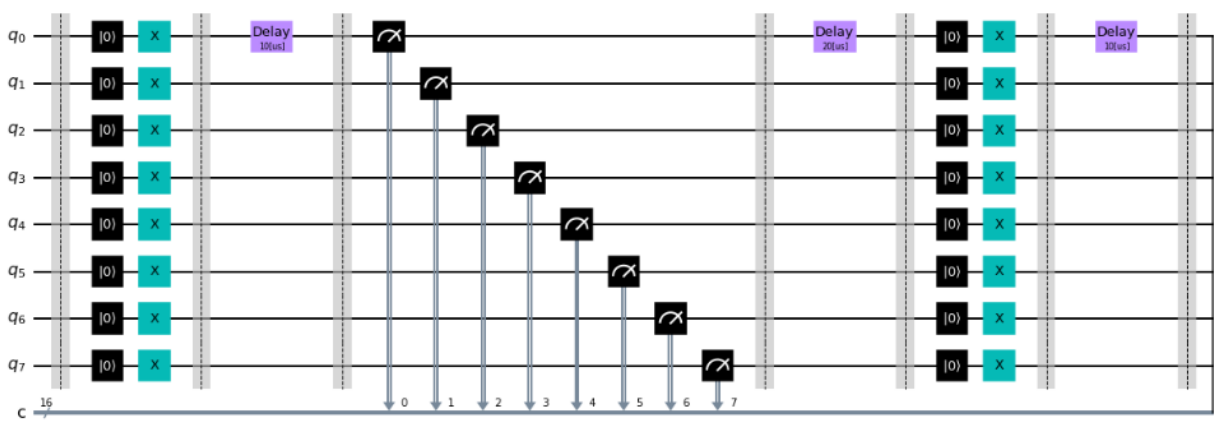

Figure 2: Our simple circuit to detect correlated qubit faults.

2-6. Findings

ICPMS assay of qubit devices found them to be very radiopure: 6.5 ± 1.2 μBq/kg ^{232}Th and 14 ± 3 μBq/kg ^{238}U. Predicted backgrounds for devices operated in the underground fridge are summarized in the Table 1. The dominant source is the "interposer" board used to connect the qubit device to external circuits. That alone contributes a background similar to the background removed by the lead shield. Identificaiton or development of clean interposer board materials will have to be done in the future to control radiation backgrounds. An interesting conclusion from this background evaluation is that in a typical qubit device, the rates of events due to cosmic rays, environmental gammas, and events from decays in the interposer are all the same order of magnitude. Many observations of qubit faults are attributed to cosmic rays based on rough calculations that the oberved rate is about right. There is no broad awareness of our somewhat surprising result yet, and attributions to cosmic rays might be wrong given the imprecise estimates. For example, the “catastrophic” chip-wide error rates attributed to cosmic rays by [3] could be caused only by gamma rays or interposer events.

The first step in testing our second hypothesis was to reproduce the observations of catastrophic correlated error bursts observed on Google hardware in [3] on IBM hardware to which we had access. We were not successful. As it turns out, that result was correct and not a deficiency of our method as we suspected at the time. Our results are shown in Figure 3. Our attempts to work together with IBM on the experiment were rebuffed, and IBM has since published their own work showing that their hardware is *not* prone to catastrophic error bursts like Google’s [6]. Lacking an appropriate platform to test our hypothesis (i.e., one prone to catastriphic correlated errors), we did not pursue this further.

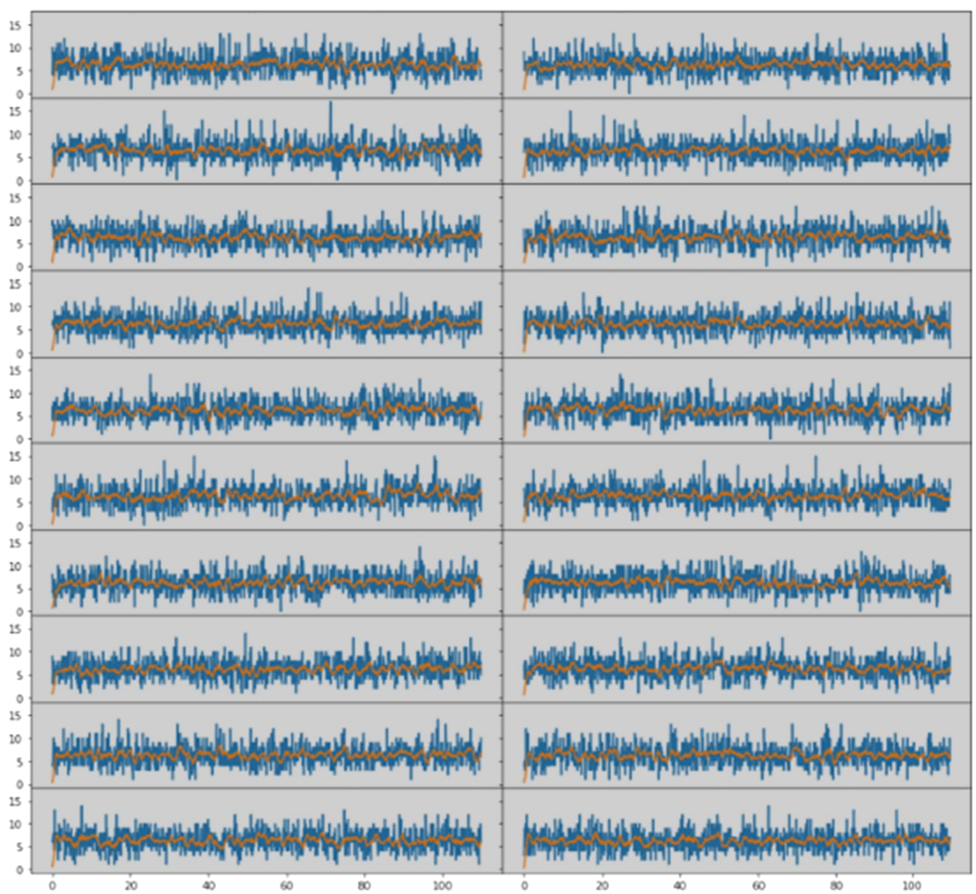

Figure 3: The results of our circuit in Figure 2. Each panel shows the number of simultaneous faults observed at 10 us delay times in a continuous 100 ms window The Orange trace is a 10-sample average. Error bursts attributable to radiation events woulkd have appeared as pulses above the average error baseline.

Table 1: Estimated background contributions in a qubit device housed in PNNL's shielded underground dilution refrigerator.

Component	Material	Mass (kg)	Interaction rate (10^{-3} cts/s/g)	Dose rate (keV/s/g)
Cosmic rays in SUL			~30	~7
Ambient gammas (no shield)			420	50
Ambient gammas (shielded)			0.8	0.1
Gamma shield (see below)			1	0.1
All DR components (see below)			0.2	0.04
All instrumentation (see below)			0.5	0.1
Ceramic PCB interposers (*Not* included in above totals)				
interposer	alumina	0.001	36	13
interposer	Rogers RO4350B	0.001	160	65
interposer	Rogers TMM10	0.001	250	92
Individual contributions to "Gamma Shield"				
Lead bricks (^{210}Pb)	Pb	6200	0.67	0.050
Inner support	Al	140	0.41	0.051
Individual contributions to "All DR components"				
MXC stage	Cu/Au	4.1	0.0032	4.4×10^{-4}
CP stage	Cu/Au	3.1	4.5×10^{-4}	5.9×10^{-5}
Still stage	Cu/Au	6.1	3.0×10^{-4}	4.0×10^{-5}
4K stage	Cu	9	8.7×10^{-5}	1.2×10^{-5}
50K stage	Cu	5	1.6×10^{-5}	2.0×10^{-6}
Vacuum flange	steel	20	7.2×10^{-4}	8.4×10^{-5}
Still can	Cu	6.8	0.0018	2.8×10^{-4}
4K can	Al	4.3	0.062	0.0086
50K can	Al	6	0.044	0.0065
Vacuum can	Al	22	0.13	0.019
Individual contributions to "All Instrumentation"				
Wirebonds	Al/Si	10×0.1 mg	0.0028	0.0012
Package	Cu	100 g	0.037	0.010
Coax connectors	MMCX	10 ct	0.37	0.11
Fasteners	brass	10×0.3 g	0.0044	0.0012
Closest coax cable	RG174	10×10 cm	1.7×10^{-4}	2.4×10^{-5}
MXC RF feedthroughs	MMCX	20 ct	0.0011	1.4×10^{-4}
MXC DC feedthroughs	Fischer conn.	2 ct	0.0026	3.1×10^{-4}
Readout amps, etc.	resistor	100 ct	1.3×10^{-5}	1.6×10^{-6}
Experiment stage	Cu/Au	2.1	0.015	0.0022
Experiment shield	Cu/Al/mumetal	3	0.11	0.014

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