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Spectroscopic measurements and models of energy deposition in the substrate of quantum circuits by natural ionizing radiation

Naturally occurring background radiation is a potential source of correlated decoherence events in superconducting qubits that will challenge error-correction schemes. To characterize the radiation environment in an unshielded laboratory, we performed broadband, spectroscopic measurements of background events in silicon substrates located inside a millikelvin refrigerator, an environment representative of superconducting qubit systems. We measured the background spectra in silicon substrates of two thicknesses, 500 µm and 1500 µm, and obtained the average event rate and the integrated power deposition. In a 25mm^2 area and the 500 µm substrate, these values are 0.023 events per second and 4.9 keV s^−1, respectively, counting events that deposit at least 40 keV. We find that the spectrum of background events is nearly featureless, and its intensity decreases by a factor of 40 000 between 100 keV and 3 MeV for silicon substrates 500 µm thick. We find the cryogenic measurements to be in good agreement with predictions based on simple measurements of the terrestrial gamma-ray flux outside the refrigerator, published models of cosmic-ray fluxes, a crude model of the cryostat, and radiation-transport simulations. No free parameters are required to predict the background spectra in the silicon substrates. The good agreement between measurements and predictions allows confident assessment of the relative contributions of terrestrial and cosmic background sources and their dependence on substrate thickness. Our spectroscopic measurements are performed with superconducting microresonators located on micromachined silicon islands that define the interaction volume with background radiation. The resonators transduce deposited energy to a readily detectable electrical signal. Microresonator readout closely resembles dispersive superconducting qubit readout, so similar devices—with or without micromachined islands—are suitable for integration with superconducting quantum circuits as detectors for background events. We find in our specific laboratory conditions that gamma-ray emissions from radioisotopes are responsible for the majority of events depositing E <1.5 MeV, while nucleons among the cosmic-ray secondary particles cause most events that deposit more energy. We discuss lessons learned from the construction of an accurate model of background radiation. We also discuss implications for the efficacy of several strategies to reduce the impact of background radiation on quantum circuits. Finally, we discuss logical follow-on work.

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