Terrestrial cosmic-ray energy deposition in superconducting qubits and its impact on quantum computing

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ABSTRACT

Terrestrial cosmic rays originate from high-energy galactic cosmic rays interacting with Earth's atmosphere, producing extensive showers of secondary particles (protons, neutrons, muons, electrons, positrons, gamma rays, and others) [1]. This radiation environment poses significant reliability challenges for both classical and quantum electronic systems. In modern microelectronics, for example, atmospheric neutrons are the primary cause of destructive failures in transistors [2], [3]. In superconducting quantum circuits, while the particle species that most contribute to severe decoherence are still under debate, it is clear that environmental radiation is a key threat to the performance of next-generation quantum processors [4].

Achieving superconducting quantum bits (qubits) with long coherence times is essential for reliable quantum information processing. However, experiments reveal quasiparticle densities well above thermal equilibrium predictions [4]. This excess has been attributed to interactions with terrestrial cosmic rays and radioactive decay products [5−8]. When such radiation penetrates through the qubit chip substrate (typically silicon or sapphire), it deposits energy and generates high-energy phonons. Upon reaching the superconducting film, phonons with energy exceeding twice the superconducting gap ($E_p > 2\Delta$) can break Cooper pairs into quasiparticles. These quasiparticles subsequently tunnel through Josephson junctions, causing energy decay and dephasing that degrade qubit coherence [7].

Accurately modeling the radiation-induced qubit decoherence requires a detailed understanding of both the local radiation environment and the mechanisms by which deposited energy is converted into phonons in the superconducting chip substrate at millikelvin temperatures. A key quantity linking radiation to subsequent phonon generation is the mean energy required to create a single electron-hole pair (ε) in the substrate material. According to the Shockley model [9], ε exceeds the bandgap energy because a portion of the deposited energy is inevitably converted into phonons. This process involves a competition between optical phonons produced by hot-carrier impact ionization cascades, and phonons generated by the dissipation of residual energy from carriers that no longer have sufficient energy to ionize the lattice [10]. Therefore, from ε, one can estimate the average number of phonons generated per radiation-induced electron-hole pair. Despite its importance, the value of ε for candidate qubit substrates remains unknown at millikelvin temperatures, the regime typical of superconducting qubit operation, and data are scarce even at low temperatures.

In this work, we investigate the microscopic mechanisms and dynamics of cosmic-ray energy deposition in superconducting qubits and the resulting consequences for quantum computing applications. First, by using a particle detector with thickness representative of superconducting qubit chip substrates, we developed a prototype designed to measure $\varepsilon(T)$ and estimate radiation-induced phonon production at low temperatures. We then perform computational simulations of the atmospheric radiation field at selected locations, validating our model against reference measurements of atmospheric neutron flux [11]. After validation, we simulate the atmospheric radiation field at a Brazilian quantum device physics laboratory and discuss how the phonon-to-quasiparticle downconversion model [7] can be combined with simulations to estimate the number of quasiparticles induced by a single primary radiation-induced phonon. This approach enables us to evaluate the impact of the full simulated radiation spectrum, including discrimination by particle species, on qubit decoherence.

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