Tradeoff between Leakage and Dephasing Errors in the Fluxonium Qubit[1]

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Superconducting circuits are a promising technology for building scalable quantum processors in the solid-state [2]. They feature a tunable anharmonic spectrum that can be used as a two-level system, defining a qubit. Single- and two-qubit gates have been demonstrated [3–5] and the lithographic fabrication process is a mature technique, allowing for large scale production. However, as a general rule, solid state qubits couple much more strongly to their surrounding environments than systems such as atoms or photons, leading to far shorter decoherence times. Considerable effort has thus been invested in fighting the causes of decoherence in different superconducting circuits [6–11], in order to attempt to bring achievable error rates close to fault-tolerant thresholds. Importantly, recent experimental advances point to pure dephasing (i.e. dephasing without population relaxation) as a significant source of decoherence in superconducting qubits coupled to a cavity [12–14]. In particular, in cases where relaxation processes can be greatly reduced [11, 14, 17], pure dephasing can lead to decoherence (T_2) times that are significantly shorter than the lifetime limit of $2T_1$.

We present a tradeoff between anharmonicity (related to leakage) and pure dephasing errors for the fluxonium circuit. We show that in the insulating regime, i.e., when the persistent current flowing across the circuit is suppressed, the pure dephasing rate induced by a Markovian environment decreases exponentially as the impedance of the circuit is increased. At larger values of the circuit's impedance, the lowest-lying states are better approximated by harmonic oscillator states in the insulating regime, and the transition from the insulating to the superconducting phases occurs at increasing values of the ratio E_J/E_C. The independence of the harmonic oscillator states to external flux variations can thus be inherited by the fluxonium states, though without a complete loss of anharmonicity necessary to define a qubit. In other words, in contrast to this exponential decrease, the qubit remains sufficiently anharmonic so that gate times can still be short, allowing for significant reduction in the computational error rates. A transition from the insulating to superconducting phases establishes an upper bound on the Josephson energy below which this tradeoff exists.

Experimental advances towards realisation of very high impedances [18], as well as towards to the inhibition of relaxation processes in 3D cavities [11, 14], make our result relevant in the design of the next generation of superconducting qubits. This result is also interesting for the design of a topologically protected superconducting mirror qubit [21], in which a degenerate ground state is used to encode a qubit and the source of decoherence is expected to be mainly due to a lifting of this degeneracy.

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