**Giant Improvements in Coherence Time for Superconducting Qubits**

*Superconducting qubit in waveguide cavity with coherence time approaching 0.1ms*

*arXiv:1202.5533*

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It is possible, in principle, to build a fault-tolerant quantum computer which will still function correctly even if its qubits and gate operations are imperfect. If the error rate per gate operation is below some threshold, fault tolerance can be successfully and stably implemented by concatenation of quantum error correction steps (even when the error correction operations themselves are imperfect). The particular error rate threshold depends on details of the implementation but is generally in the range of $10^{-5}$ per operation, although so-called 'surface codes' may tolerate errors in the $\sim 10^{-1}$ range [1]. If the dominate source of errors is qubit decoherence, the error rate per gate is approximately the gate operation time divided by the coherence time. For superconducting qubits, current values for single qubit gate errors are in the $\sim 10^{-3}$ range and two-qubit gate errors are in the $\sim 10^{-2}$ range.

What are the ultimate limits on the coherence time of superconducting qubits? The short answer is that we still don't know. Through clever qubit design and microwave circuit engineering, phase coherence times for superconducting qubits have advanced a remarkable five orders of magnitude in the last dozen years. Coherence can be destroyed by dissipative processes in which the qubit makes a transition between the excited state and the ground state (or vice versa). It can also be destroyed by quasi-elastic dephasing processes which cause the qubit transition frequency to fluctuate in time. These fluctuations have been attributed to glassy dynamics of two-level defects in the environment, motion of trapped flux quanta within the superconducting circuit and other poorly understood fluctuations in the qubit Hamiltonian. As described below, recent experiments with minimalist circuit designs with very long coherence times suggest that we still have not yet reached any intrinsic limits set by materials properties, but rather are still limited by imperfect 'microwave hygiene.'

The phase coherence time $T_2^*$ measured in a Ramsey interference experiment is given by $1/T_2^* = 1/2T_1 + 1/T_\varphi$ where $1/T_1$ is the energy relaxation rate and $1/T_\varphi$ is the pure dephasing rate. (The peculiar factor of two in the first term is related to the fact that $1/T_1$ is a probability decay rate and $1/T_2$ is an amplitude decay rate.) If the fluctuations in the transition frequency are slow on the time scale of $T_2^*$, then they can be echoed away by inserting an extra pi pulse into the middle of the Ramsey sequence which gives a coherence time $T_2 > T_2^*$. Recent theoretical advances have led to more complex echo sequences which can in principle further enhance the coherence times [2,3] in the presence of smoothly varying fluctuations of the qubit frequency.

Superconducting qubits have transition frequencies in the microwave domain. One possible source of energy relaxation is dielectric loss in the Josephson junction tunnel barrier or the surrounding substrate and circuitry. The other possible source is spontaneous emission of microwave photons which are carried away by transmission line modes of the circuit. The qubit can be protected against spontaneous emission by placing it inside a resonator which filters out the vacuum noise from the continuum at the qubit transition frequency. This so-called Purcell effect has been demonstrated in co-planar waveguide resonator structures [4] where phase coherence times of 1-2 microseconds for transmon qubits have become routine. (A transmon qubit is a very simple qubit consisting of two wires forming a short dipole antenna connected via a Josephson junction.) By placing a transmon qubit on a sapphire substrate inside a high-quality-factor three-dimensional superconducting cavity resonator which more fully protects the qubit from the electromagnetic environment, Paik et al. [5] recently made a revolutionary advance in coherence times. Reproducible $T_1$ times in the $30 - 60\mu$s range and phase coherence times up to $\sim 20\mu$s without echo were demonstrated. Even higher coherence times have been demonstrated recently [6,7] and reproduced at several labs around the world. Most recently the IBM group of Rigetti et al. has demonstrated realization of a phase coherence time of $95\mu$s without echo, also using the same setup of a transmon in a 3D cavity. These coherence times represent an advance of superconducting qubits by some five orders of magnitude in little more than a decade.

There is now very strong evidence that the residual dephasing in the 3D circuits is caused by stray photons entering the cavity. When detuned from the cavity, qubits have a dispersive coupling to the photon number of the form

$$V = \sum_j \chi_j \sigma^z a_j^\dagger a_j, \tag{1}$$

where $2\chi_j$ is the 'light shift' of the qubit transition frequency caused by each photon present in the $j$th cavity mode. In the IBM experiment, Rigetti et al. took a number of precautions against stray photons and used a qubit with relatively small values of the $\chi_j$ to help reduce the dephasing rate. By lowering the cavity output coupling in situ (and thus increasing the cavity lifetime), the Yale group has demonstrated that the dephasing noise slows down and echo pulses become more effective [7]. This confirms that it is stray photons which are causing the dephasing, because the time scale on which they jump in and out of the cavity increases with the cavity lifetime.

With even more extreme microwave filtering this source of pure dephasing should be straightforward to eliminate and the hunt for the remaining sources of relaxation and dephasing can continue.

**References:**


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