I. INTRODUCTION

Superconducting qubits are attractive candidates for realizing a practical quantum computer. In particular, the Josephson junction is the only known non-linear, non-dissipative electrical circuit element, making it an ideal building block for quantum computation. The lack of intrinsic dissipation holds the promise of long coherence times while non-linearity is integral to high-fidelity quantum measurement. Significant recent progress has resulted in the initial demonstration of a controlled-not gate [1] and state tomography of coupled qubits [2]. What remains unclear at present are the sources that limit coherence—both the energy relaxation time T_1 and the dephasing time T_2^*—in these qubits. Here T_2^* is the dephasing time obtained without a correcting echo sequence. For further progress, it is critical that T_1 and T_2^* be increased by 1-2 orders of magnitude to attain the necessary number of operations ($> 10^4$) to implement error correction.

We are investigating a new type of highly symmetric superconducting qubit with tetrahedral symmetry. This “tetrahedral qubit” has been predicted to be highly noise resistant, by virtue of being intrinsically protected from external sources of decoherence originating, for example, from materials defects or from the measurement circuitry. Given the massive overhead involved in fault-tolerant quantum computation, such intrinsically *noise resistant* qubits may play an essential role in scalable quantum computing.

This effort complements materials research elsewhere by maximizing the coherence times attainable with a given material, and thus reducing the quality control requirements on advanced materials for superconducting qubits. To realize $T_1 \approx 100$ μs in an unprotected qubit such as a superconducting phase or charge qubit one would require a defect density of 1 part in 10^8 or better over a 1 mm^2 sized area, which is a challenging task. In this proposal, a superconducting qubit with tetrahedral symmetry proposed by Mikhail Feigelman, Lev Ioffe and co-workers [3] is considered. Such a qubit may approach a relaxation time of 100 μs using currently available materials. The proposed research is a first step towards implementing coherent manipulations in a superconducting tetrahedral qubit.

II. TETRAHEDRAL QUBIT

The tetrahedral qubit consists of four superconducting islands with six Josephson junctions. A schematic of the proposed device geometry is shown in Figure 1. Three islands are arranged in a triangular loop while the fourth island provides a phase reference and is in the shape of a ring which forms the outside boundary of the qubit, rendering the structure topologically equivalent to a tetrahedron. Three to six Josephson junctions are needed to perform a measurement of the qubit. In Figure 1, a fully symmetric arrangement with six junctions is illustrated. Each of the inner islands has to be charge biased with 1/2 Cooper pair of offset charge and each of the three loops has to be frustrated with a magnetic flux of $\Phi_0/2$, which will be applied through a static, global magnetic field. The charge and local flux correction biasing will be accomplished through microwave coplanar waveguide planar transmission lines, shown as green and grey structures, respectively, in Figure 1. These lines will be fabricated first and then covered with a dielectric layer, such as silicon nitride, on top of which the qubit and measurement circuitry will be deposited.

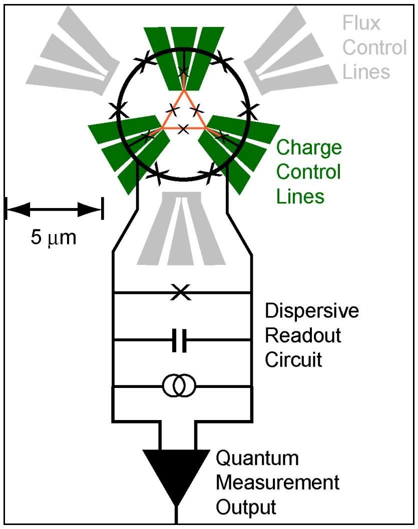

Figure 1: Schematic of the tetrahedral qubit with a non-linear dispersive readout. The qubit has three islands in a triangular loop surrounded by a circular fourth island. Each branch inside the loop is interrupted with a Josephson junction with $E_J/E_C \sim 100$. The green and grey microwave transmission lines provide the charge and flux bias, respectively, for the qubit. These lines are located in an electrically isolated layer below the qubit and readout circuitry. The outer ring-shaped island has six larger junctions for measurement coupled to a non-linear measurement circuit, similar to that used in the bifurcation amplifier for the Quantronium qubit.

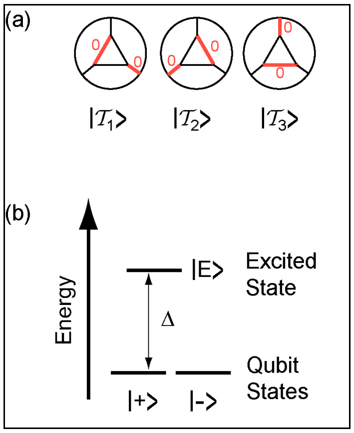

Figure 2: (a) Basis states $|T_1>$, $|T_2>$, and $|T_3>$ for the tetrahedral qubit. The red lines represent junctions with 0 phase difference; all others have π phase difference. (b) The qubit states are linear combinations of the basis states with $|+> = [|T_1> + e^{2\pi i/3}|T_2> + e^{-2\pi i/3}|T_3>]/\sqrt{3}$ and $|-> = [|T_1> + e^{-2\pi i/3}|T_2> + e^{2\pi i/3}|T_3>]/\sqrt{3}$. The next higher energy state is a singlet separated by energy Δ.

In addition to biasing the qubit with static fields, these control lines will also be used to apply microwave pulses to prepare and manipulate the state of the qubit, as is done in other superconducting qubits. What is different in the tetrahedral qubit is that these microwave pulses are not applied at the Larmor frequency, since the qubit states are degenerate in energy. An energy level diagram of the qubit states is shown in Figure 2. The two qubit states are linear combinations of three basis states, each of which involves two junctions with 0 phase difference and four junctions with π phase difference. These combinations are analogous to the symmetric and anti-symmetric combinations of states with definite charge or flux. To flip the state of the tetrahedral qubit, a control pulse shuffles the flux bias of the loop. To avoid excitations out of the state space, the maximum speed with which a bit flip can be accomplished is set by the energy gap Δ to the singlet state, and is typically ~ 10 GHz, which should permit $> 10^5$ operations.

Though the tetrahedral qubit requires a more sophisticated fabrication procedure than some other superconducting qubits, it has excellent potential for scalability because the design consists of junctions that are ~ 1 μm in size and that can readily be produced with 5% or better critical current spread. Small variations in junction parameters can be offset by applying a static magnetic flux. Moreover, there are no Larmor frequencies to synchronize, which is a major challenge in conventional superconducting qubits. Also, unlike in phase qubits, there are no capacitors to fabricate, avoiding a potential major source of decoherence.

III. QUBIT COHERENCE

The tetrahedral qubit is protected to first order against low frequency fluctuations in charge and flux [3]. The magnitudes of all of these noise sources may be reduced using materials science. Using current materials, we can estimate the maximum T_2^* times that should be attainable now. For junctions with $E_J/E_C \sim 100$, biased at the 1/2 Cooper pair degeneracy point, both charge noise and critical current noise are negligible. The dominant source of noise will be flux noise, but this couples much more weakly in the tetrahedral qubit than in the flux qubit. Overall, a range $T_2^* \sim$ 10-100 μs is predicted. Part of the theoretical component of our work will be to improve on these rough estimates and generate detailed predictions for the coherence time and how to optimize this.

In terms of T_1, superconducting qubits suffer from relaxation due to imperfections in the microwave environment in which they are embedded. The tetrahedral qubit is unique in that it would not couple to such defects because of its doubly degenerate ground-state. In this case, a simple estimate for T_1 can be made from the 50 ohm microwave environment of the control lines. From this, one estimates that $T_1 \sim 100$ μs should be attainable.

In addition to longer coherence times, topological qubits such as the tetrahedral qubit would permit more complex computing schemes such as those based on Berry's phase. Gate operations which rely only on the path executed by a system are predicted to have a built-in fault tolerance to certain errors [10]. The existence of such geometric phases has already been demonstrated in nuclear magnetic resonance experiments. Tetrahedral qubits have the potential for this type of quantum computation when the external control parameters are adiabatically varied (<< Δ/h). This would be a first step to realizing fully topologically protected qubits of the non-Abelian anyon type, e.g., from arrays of Josephson junctions [9] built using the same technological principles that will be developed here for the tetrahedral qubit.