Superconducting Circuits and Quantum Computation

RLE Group
Superconducting Circuits and Quantum Computing Group

Academic and Research Staff
Professor Terry P. Orlando

Postdoctoral Students
Dr. Yang Yu, Dr. Jonathan Habif

Collaborators
Prof. Leonid Levitov, Prof. Seth Lloyd, Prof. Johann E. Mooij [1], Dr. Juan J. Mazo [2], Dr. Fernando F. Falo [2], Prof. Karl Berggren, Prof. M. Tinkham [4], Dr. Sergio Valenzuela [4], Prof. Marc Feldman [5], Prof. Mark Bocko [5], Dr. William Oliver [3], Dr. Zachary Dutton [6], Dr. Donald S. Crankshaw [3]

Visiting Scientists and Research Affiliates
Dr. Juan Mazo [2], Prof. Johann E. Mooij [1], Dr. Kenneth J. Segall [7]

Graduate Students
Daniel Nakada, Murali Kota, Janice Lee, David Berns, William Kaminsky, Bryan Cord

Undergraduate Students
Andrew Clough

Support Staff
George D. Hall

Introduction

Superconducting circuits are being used as components for quantum computing and as model systems for non-linear dynamics. Quantum computers are devices that store information on quantum variables and process that information by making those variables interact in a way that preserves quantum coherence. Typically, these variables consist of two quantum states, and the quantum device is called a quantum bit or qubit. Superconducting quantum circuits have been proposed as qubits, in which circulating currents of opposite polarity characterize the two quantum states. The goal of the present research is to use superconducting quantum circuits to perform the measurement process, to model the sources of decoherence, and to develop scalable algorithms. A particularly promising feature of using superconducting technology is the potential of developing high-speed, on-chip control circuitry with classical, high-speed superconducting electronics. The picosecond time scales of this electronics means that the superconducting qubits can be controlled rapidly on the time scale and the qubits remain phase-coherent.

Superconducting circuits are also model systems for collections of coupled classical non-linear oscillators. Recently we have demonstrated a ratchet potential using arrays of Josephson junctions as well as the existence of a novel non-linear mode, known as a discrete breather. In addition to their classical behavior, as the circuits are made smaller and with less damping, these non-linear circuits will go from the classical to the quantum regime. In this way, we can study the classical-to-quantum transition of non-linear systems.

[1] Delft University of Technology, The Netherlands
[2] University of Zaragoza, Spain
[3] M.I.T. Lincoln Laboratory
[4] Harvard University
[5] University of Rochester
[6] NIST, Gaithersburg
[7] Colgate University

1. Superconducting Persistent Current Qubits in Niobium

Sponsors
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Project Staff
Yang Yu,, Jon Habif, Daniel Nakada, Janice C. Lee, David Berns, Bryan Cord, and Sergio Valenzuela (Harvard); Professors Terry Orlando, Karl Berggren, Leonid Levitov, Seth Lloyd and Professor Michael Tinkham (Harvard)

Quantum Computation combines the exploration of new physical principles with the development of emerging technologies. In these beginning stages of research, one hopes to accomplish the manipulation, control and measurement of a single two-state quantum system while maintaining quantum coherence between states. This requires a coherent two-state system (a qubit) along with a method for control and measurement. Superconducting quantum computing could accomplish this in a manner that can be scaled to a large numbers of qubits. We are studying the properties of a two-state system made from a niobium (Nb) superconducting loop, which can be incorporated on-chip with other superconducting circuits for control and measurement. The devices we study are fabricated at MIT Lincoln Laboratory, which uses a Nb-trilayer process for the superconducting elements and optical projection photolithography to define circuit features. Our system is inherently scalable but has the present challenge of being able to demonstrate appreciable quantum coherence.

The particular device under study is made from a loop of Nb interrupted by three Josephson junctions (Fig. 1a). The application of an external magnetic field to the loop induces a circulating current whose magnetic field either enhances (circulating current in the clockwise direction) or diminishes (counterclockwise) the applied magnetic field. When the applied field is near one-half of a flux quantum Φ_0, quantum superposition of both the clockwise and counterclockwise current states is possible. Thus the system behaves as a two-state system. The potential energy versus circulating current is a so-called double-well potential, with the two minima representing the two states of equal and opposite circulating current as shown in Figure 1c. The flux produced by the circulating currents can be measured by the sensitive flux meter provided by the dc SQUID.

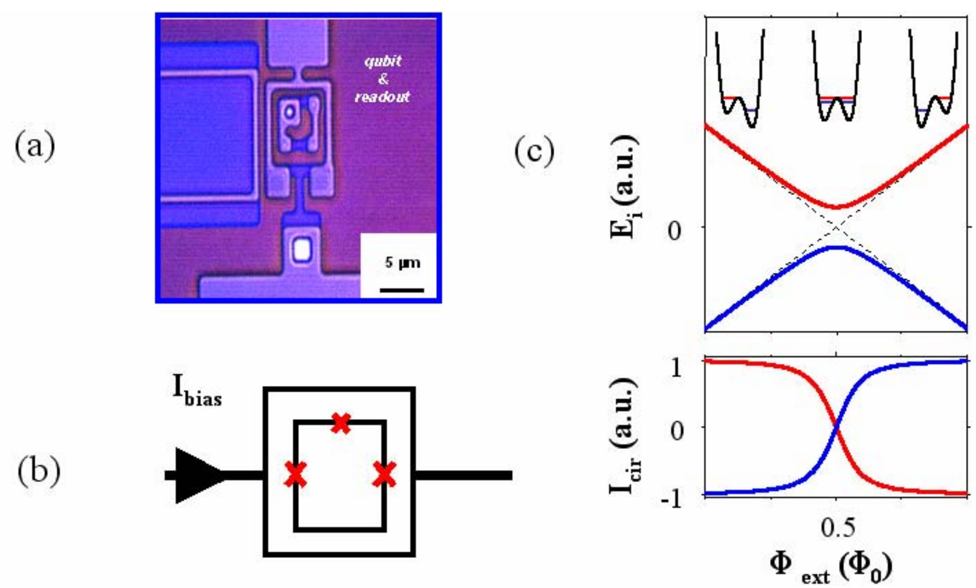

FIGURE 1. (a) SEM image of the persistent current qubit (inner loop) surrounded by the measuring dc SQUID. (b) A schematic of the persistent current qubit and measuring SQUID; the x's mark the Josephson junctions. (c) The energy levels for the ground state (dark line) and the first excited state of the qubit versus applied flux Φ_{ext}. The double well potentials are shown schematically in the above graph. The lower graph shows the circulating current in the qubit for both states as a function of applied flux (in units of flux quantum Φ_0).

2. Rapid Measurements in Superconducting Persistent Current Qubits

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Project Staff
Yang Yu, W. D. Oliver (MIT Lincoln Laboratory), and T. P. Orlando

We installed a rapid measurement setup with a band width of about 1 GHz on our dilution refrigerator. By using an ultra-fast measurement scheme, we investigated the spectroscopy of superconducting Nb persistent current (PC) qubits. The time-resolved experiments showed that the energy relaxation time between the macroscopic quantum states is about 10 μs [1, 2]. We also demonstrated the superposition of macroscopic quantum states and Rabi oscillations between two macroscopic quantum states with microwave irradiations. The long time macroscopic quantum coherence, together with the advanced fabrication technique, suggests the strong potential of realizing the quantum computing with Nb-based superconducting qubits.

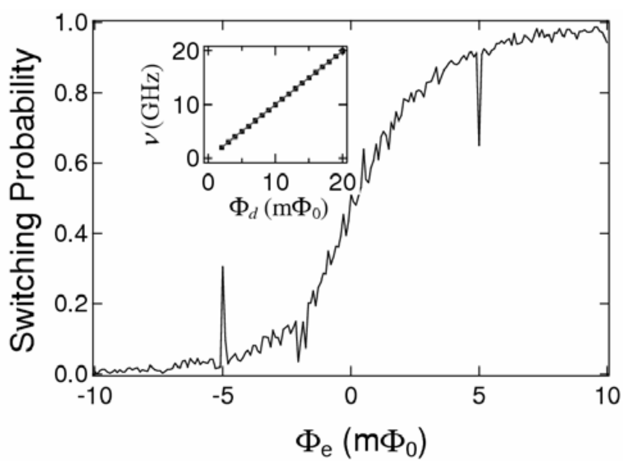

Fig. 1. Switching probability vs. external magnetic field with 10 GHz microwave irradiation. The resonant peak and the dip are caused by photon induced transition between two macroscopic quantum states. Inset: microwave frequency vs. the distance between the peak and the dip (symbols). The solid line is the theoretical calculation using qubit parameters.

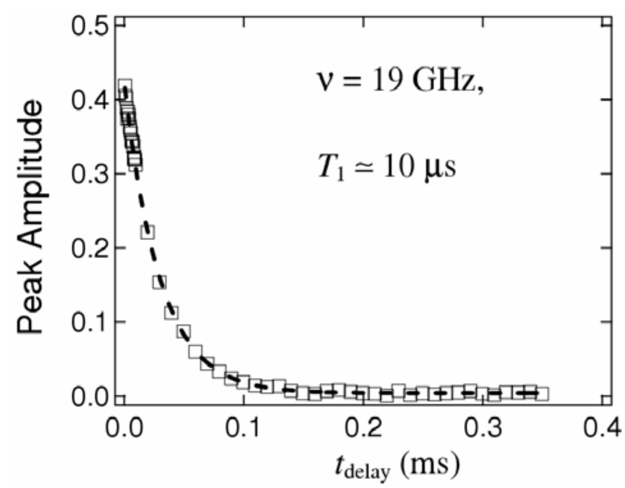

Fig. 2. Normalized resonant peak amplitude as a function of readout delay time t_{delay}. The dashed line is the best fit to exponential decay with a time constant T_1 = 10 μs. The experimental data show remarkable agreement with the theory prediction.

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3. Resonant Readout of a Persistent Current Qubit

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Project Staff
Janice C. Lee, Dr. William D. Oliver (MIT Lincoln Laboratory), Prof. Terry P. Orlando

The two logical states of a persistent current (PC) qubit correspond to oppositely circulating currents in the qubit loop. The induced magnetic flux associated with the current either adds to or subtracts from the background flux. The state of the qubit can thus be detected by a DC SQUID magnetometer inductively coupled to the qubit.

We have implemented a resonant technique that uses a SQUID as a flux-sensitive Josephson inductor for qubit readout. This approach keeps the readout SQUID biased at low currents along the supercurrent branch. The low bias reduces the level of decoherence on the qubit, and is more desirable for quantum computing applications. We incorporated the SQUID inductor in a high-Q on-chip resonant circuit, and were able to distinguish the two flux states of a niobium PC qubit by observing a shift in the resonant frequency of the readout circuit. The nonlinear nature of the SQUID Josephson inductance as well as its effect on the resonant spectra of the readout circuit was also characterized.

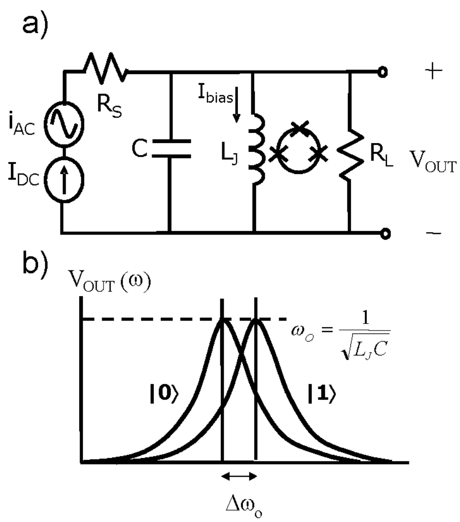

Figure 1a: The SQUID inductor is incorporated in a resonant readout circuit. It is inductively coupled to a PC qubit to detect its state. Figure 1b: A transition of the qubit state changes the Josephson inductance of the SQUID, and can be sensed as a shift in the resonant frequency of the readout circuit.

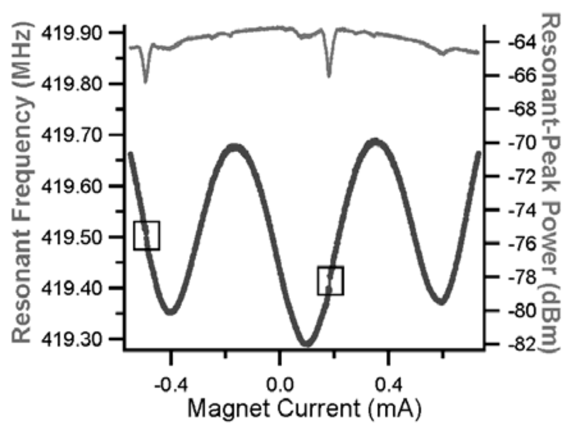

Figure 2: Experimental results at 300mK: the lower plot (left axis) shows the modulation of the resonant frequency with external magnetic field. Qubit steps corresponding to transitions between opposite flux states were observed at every 1.3 periods of the SQUID lobe. The upper plot (right axis) shows the corresponding peak amplitude of the resonant spectrum. The dip in peak power coincides with the qubit step.

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4. Measurements of a Persistent-Current Qubit driven by an on-chip radiation source

Sponsors
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Project Staff
J. L. Habif, B. Singh, D. S. Crankshaw, T. P. Orlando

State-of-the-art experiments involving superconducting qubits consist of one or two qubit systems whose quantum state is manipulated using high-bandwidth, room-temperature laboratory electronics[1]. In order to scale a superconducting quantum computer to many qubits a more efficient means of qubit manipulation is certainly necessary. The experiments conducted here investigate using a classical superconducting device integrated on-chip with the qubit to drive transitions between quantum energy levels of the qubit.

Shown in Fig. 1, the circuit consists of the on-chip oscillator on the left and the persistent-current (pc) qubit and measurement SQUID on the right. If the current bias to the oscillator is increased beyond its superconducting critical current the oscillator emits microwave radiation. Coupling between the on-chip oscillator and persistent-current qubit is inductive and mediated by a bandpass RLC filter. The quantum energy levels of the pc-qubit are tuned by applying an externally applied magnetic field. When the field is tuned so that the energy level separation in the pc-qubit matches the energy of the radiation field from the on-chip oscillator transitions can be induced between the constituent energy levels of the pc-qubit[2].

Fig. 2 shows data from the pc-qubit with the oscillator emitting radiation at four different frequencies. As the oscillator frequency is increased the magnetic flux applied to the qubit must be tuned to match the energy of the radiation. The trend shown in the data correctly corresponds to the predicted energy dependence of pc-qubit with applied magnetic flux, indicating that radiation from the on-chip oscillator is successfully driving transitions between quantum energy levels of the pc-qubit[3].

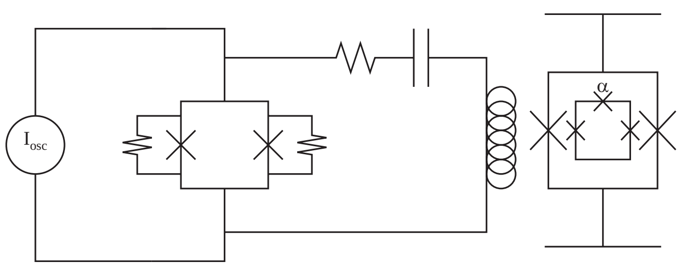

Figure 1: A schematic representation of the on-chip oscillator circuit with a bandpass filter, coupled inductively to the pc-qubit and measurement SQUID. When the oscillator is current biased above its superconducting critical current it emits radiation at a frequency that can be tuned by the current bias. The radiation can stimulate quantum transitions within the superconducting persistent-current qubit.

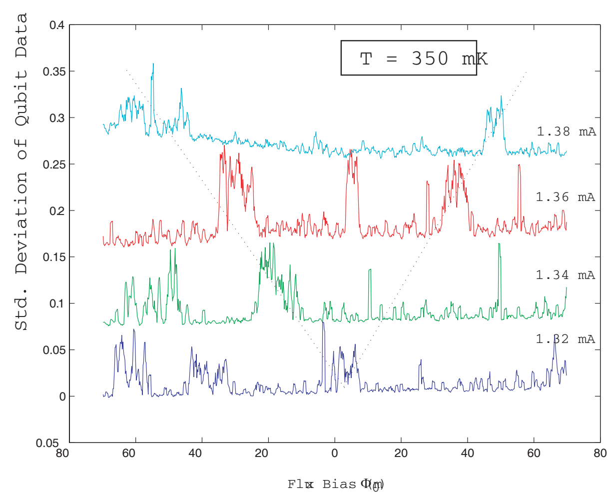

Figure 2: Data Illustrating oscillator dependent excitations in the persistent-current qubit. As the current bias to the oscillator is increase the frequency of radiation produced by the oscillator also increases, and correspondingly, the excitations in the persistent-current qubit move away from one another, matching the quantized energy levels in the device.

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5. Probing Decoherence with Electromagnetically Induced Transparency in Superconductive Quantum Circuits

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Project Staff
Kota Murali, Dr. Zachary Dutton (Naval Research Laboratory), Dr. William Oliver (MIT Lincoln Lab)
Professor Terry Orlando

Superconductive quantum circuits (SQCs) comprising mesoscopic Josephson junctions quantized flux and/or charge states are analogous to the quantized internal levels of an atom. This SQC-atom analogy can be extended to the quantum optical effects associated with atoms, such as electromagnetically induced transparency (EIT).

The three-level Λ-system for our S-EIT system (Fig.1a) is a standard energy level structure utilized in atomic EIT. It comprises two meta-stable states $|1\rangle$ and $|2\rangle$, each of which may be coupled to a third excited state $|3\rangle$. In an atomic EIT scheme, a strong “control” laser couples the $|2\rangle\rightarrow|3\rangle$ transition, and a weak resonant “probe” laser couples the $|1\rangle\rightarrow|3\rangle$ transition. By itself, the probe laser light is readily absorbed by the atoms and thus the transmittance of the laser light through the atoms is quite low. However, when the control and probe laser are applied simultaneously, destructive quantum interference between the atomic states involved in the two driven transitions causes the atom to become “transparent” to both the probe and control laser light. Thus, the light passes through with virtually no absorption. In this work we propose to use EIT in SQCs to sensitively probe decoherence.

The SQC (fig 1b) can be biased to result in an asymmetric double well potential as shown in Fig. 2. The three states in the left well constitute the superconductive analog to the atomic Λ-system. States $|1\rangle$ and $|2\rangle$ are “meta-stable” qubit states, with a tunneling and coherence time much longer than the excited “readout” state $|3\rangle$. State $|3\rangle$ has a strong inter-well transition when tuned on-resonance to state $|4\rangle$. Thus, a particle reaching state $|3\rangle$ will tend to tunnel quickly to state $|4\rangle$, causing the circulating current to switch to the other direction, an event that is detected with a SQUID. Knowing how long the SQC remains transparent (i.e., does not reach state $|3\rangle$) in the S-EIT experiment provides an estimate for the decoherence time.

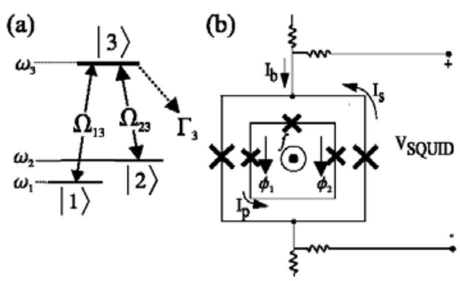

Figure 1: a. Energy level diagram of a three-level Λ system. EIT can occur in atoms possessing two long-lived states |1>, |2>, each of which is coupled via resonant laser light fields to a radiatively decaying state |3>. b. Circuit schematic of the persistent –current qubit and its readout SQUID.

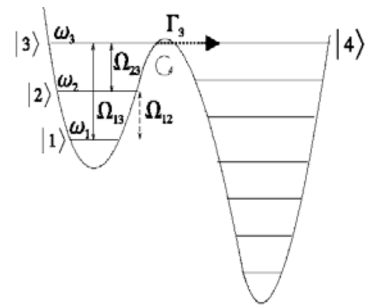

Figure 2: One-dimensional double-well potential and energy-level diagram for a three-level SQC.

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6. Type-II Quantum Computing Using Superconducting Qubits

Sponsors

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Project Staff

David Berns, William M. Kaminsky, Bryan Cord, Karl Berggren, Dr. William Oliver (MIT Lincoln Laboratory), Terry P. Orlando

Most algorithms designed for quantum computers will not best their classical counterparts until they are implemented with thousands of qubits. For example, the factoring of binary numbers with a quantum computer is estimated to be faster than a classical computer only when the length of the number is greater than about 500 digits [1]. In contrast, the Factorized Quantum Lattice-Gas Algorithm (FQLGA) [2] for fluid dynamics simulation, even when run on a quantum computer significantly smaller than the one just discussed, has significant advantages over its classical counterparts.

The FQLGA is the quantum version of classical lattice-gases (CLG)[3]. CLG are an extension of classical cellular automata with the goal of simulating fluid dynamics without reference to specific microscopic interactions. The binary nature of the CLG lattice variables is replaced for the FQLGA by the Hilbert space of a two-level quantum system. The results of this replacement are similar to that of the lattice-Boltzmann model, but with a few significant differences [4]. The first is the exponential decrease in required memory. The second is the ability to simulate arbitrarily small viscosities.

We have recently developed two implementations of the algorithm for the 1D diffusion equation using the PC Qubit. The first consists of initializing the qubits while keeping them in their ground state, and then performing the collision by quickly changing their flux bias points and then performing a single $\pi/2$ pulse(Fig.1). This initialization technique could prove quite useful, since relaxation effects are avoided, but the way we have implemented the collision is not easily generalized to other collisions. A more general collision implementation was then developed by decomposing the unitary collision matrix into a sequence of single qubit rotations and coupled free evolution. The single qubit rotations then also serve to initialize the fluid's mass density.

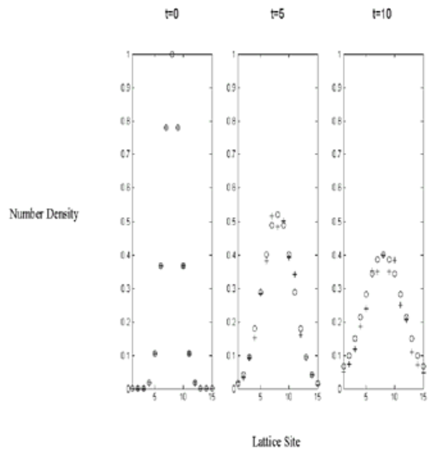

Fig.1. Simulation of the FQLGA for 1D diffusion is pictured(o) alongside simulation of the first proposed implementation(+). The expected diffusion of a gaussian is observed.

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7. Scalable Superconducting Architecture for Adiabatic Quantum Computation

Sponsors
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Project Staff
W. M. Kaminsky, S. Lloyd, T. P. Orlando

Adiabatic quantum computation (AQC) is an approach to universal quantum computation in which the entire computation is performed in the ground state of a suitably chosen Hamiltonian [1]. As such, AQC offers intrinsic protection against dephasing and dissipation [2,3]. Moreover, AQC naturally suggests a novel quantum approach to the classically intractable constrained minimization problems of the complexity class NP. Namely, by exploiting the ability of coherent quantum systems to follow adiabatically the ground state of a slowly changing Hamiltonian, AQC promises to bypass automatically the many separated local minima occurring in difficult constrained minimization problems that are responsible for the inefficiency of classical minimization algorithms. To date, most research on AQC [4-8] has focused on determining the precise extent to which it could outperform classical minimization algorithms. The tantalizing possibility remains that---at least for all practical purposes---AQC offers at least a large polynomial, and often an exponential, speedup over classical algorithms. However, it may be the case that in the same way the efficiency of many practical classical algorithms for NP problems can only be established empirically, the efficiency of AQC on large instances of classically intractable problems can only be established by building a large-scale AQC experiment.

To make feasible such a large-scale AQC experiment, we have proposed a scalable architecture for AQC based on the superconducting persistent-current (PC) qubits [9,10] already under development here at MIT. As first proposed in [11], the architecture naturally incorporates the terms present in the PC qubit Hamiltonian by exploiting the isomorphism [12] between antiferromagnetic Ising models in applied magnetic fields and the canonical NP-complete graph theory problem Max Independent Set. Such a design notably removes any need for the interqubit couplings to be varied during the computation. Moreover, since Max Independent Set remains NP-complete even when restricted to planar graphs where each vertex is connected to no more than 3 others by edges, a scalable programmable architecture capable of posing any problem in the class NP may simply take the form of a 2D, hexagonal, square, or triangular lattice of qubits. Finally, the latest version of the architecture [13] permits interqubit couplings to be limited to nearest-neighbors and qubit measurements to be inefficient.

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