# Proposed Experiments to Test the Foundations of Quantum Computing

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***Abstract*—Quantum computing promises computational performance that is exponentially faster than any conceivable classical computer. This is due to the theoretically expected scaling of N entangled qubits, with parallel evolution of $2^N$ quantum states. This is in sharp contrast to classical computing, where N bits may have $2^N$ classical states, but only one at a time. It is widely believed that quantum superposition and entanglement have been demonstrated in several experimental systems, and that practical quantum computing can be achieved once sufficiently long quantum relaxation times are obtained. On the contrary, we suggest that there may be serious problems with quantum computing on both the macroscopic and microscopic levels, and that the experiments thus far have not proven the existence of non-classical superposition states, which are necessary for the proper functioning of qubits. In order to investigate this further, we propose new experiments in three physical systems: electron spins, single photons, and superconducting loops. We further suggest that certain more limited classes of quantum computing, such as quantum annealing, do not require quantum entanglement, and can achieve significant performance enhancements even if universal quantum computing proves to be impossible.**

**Keywords—Spin, Qubits, Josephson junctions, Magnetic flux, Quantum computing, Quantum entanglement.**

## I. Introduction

Quantum Computing applies the mathematical formalism of quantum mechanics, developed for describing the behavior of electrons in atoms, to electronic devices on the macroscopic scale [1]. A major developing technology for quantum computing is based on integrated circuits of superconducting devices known as Josephson junctions, operating at ultra-low temperatures much less than 1 K [2,3,4,5]. It is important to distinguish classical computing based on superconducting circuits, from quantum computing, even though some of the circuits are similar [6].

In the classical case, a superconducting bistable circuit constitutes a classical bit for logic and memory, which can be either a '0' or a '1'. In contrast, in the quantum case, a similar circuit can be simultaneously in both states, which is incompatible with classical realism. This "superposition state" constitutes a quantum bit or "qubit". Furthermore, N qubits may be coupled together to form a simultaneous superposition of all $2^N$ classical digital states, a phenomenon known as "quantum entanglement." It is the massive parallelism enabled by this entangled state that gives quantum computing its tremendous computational ability, which is unachievable by any classical computer [1]. For example, if N=100 qubits, $2^{100} \sim 10^{30}$, far greater than the parallelism that can be achieved classically by duplicating hardware.

When promises for a scientific breakthrough are this revolutionary, they should be subject to an especially high barrier for acceptance. Unfortunately, these projections are largely accepted without question in the computing community, in part because the foundations of quantum mechanics are poorly understood among computer scientists and engineers (and even among physicists!).

In the present paper, we will review the foundations of quantum mechanics relevant to quantum computing, focusing first on simple model systems such as single electrons and single photons. Then, we will review the experimental measurements claiming to prove the existence of superposition and entanglement in electronic circuits. We agree with others [7] who have shown that purely classical simulations *without superposition or entanglement* can explain many of the observations, particularly in superconducting qubits. Without a clear understanding of such experimental tests, the efforts to achieve practical quantum computing may fall short of predictions, or even fail completely.

Another important consideration is that not all approaches to quantum computing are the same. A universal digital quantum computer that takes full advantage of quantum entanglement may be most promising [8], but is also the most difficult to implement. In contrast, a quantum annealer is an analog special-purpose quantum computer that is designed to solve certain optimization problems [5]. This may be less powerful than a universal quantum computer, but it is far easier to implement. In fact, a superconducting quantum annealer is already on the market, and its performance is being evaluated. In the analysis below, we will address the impact of quantum entanglement on the performance of different classes of quantum computers.

Finally, we propose new experiments in several systems (electrons, photons, and superconducting loops) that may help to address whether the revolutionary predictions of quantum computing may be achievable in realistic physical systems. Some of this material was presented earlier [9,10], but not published.

## II. Quantum Superposition and Entanglement

It is well known that states in quantum mechanics have discrete values of energy and other parameters, rather than the continuous values permitted in classical mechanics. While there may be more than two such states in many cases, the important issues can be illustrated using models with two states, which also provide the basis for qubits. Consider a physical element on the microscopic or macroscopic scale with two discrete quantum states, $\Psi_0$ and $\Psi_1$. For example, this may represent an electron in a magnetic field H, which has a magnetic moment $\mu_m$ that may be either aligned or anti-aligned with the field (Fig. 1). The anti-aligned configuration is the ground state $\Psi_0$, and the aligned configuration the excited state $\Psi_1$. Thus far, this is equivalent to a classical magnet that is used to store a single bit of information, a '0' or a '1' associated with $\Psi_0$ or $\Psi_1$.

However, according to the standard Hilbert-space model of quantum mechanics, a state in quantum mechanics is fundamentally indeterminate until it has been measured. Rather than being in either $\Psi_0$ or $\Psi_1$, the physical state is given by

$$\Psi = c_0 \Psi_0 + c_1 \Psi_1, \tag{1}$$

where $c_0$ and $c_1$ are complex numbers normalized so that $|c_0|^2 + |c_1|^2 = 1$. This approach was inspired in part by linear algebra, together with Fourier analysis, where any periodic wave can be viewed as a linear superposition of different sine waves. Here, $\Psi_0$ and $\Psi_1$ represent basis vectors in an abstract two-dimensional "Hilbert space". But unlike classical waves, $\Psi$ has a statistical interpretation, which stems from the uncertainty principle.

This is the origin for the statement that a qubit can simultaneously have two different states. If the magnetic moment is measured on an ensemble of identical electrons given by Eq. (1), the results will be a statistical mixture of $\Psi_0$, with probability $P_0 = |c_0|^2$, and $\Psi_1$, with probability $P_1 = |c_1|^2$. Within the orthodox interpretation, this statistical mixture is not an indication of variable underlying parameters. Instead, the physical state of the quantum system before measurement is in this linear superposition of two states, a vector in a 2D Hilbert space, which can evolve in time as long as it remains "coherent". Note that a classical magnetic bit may switch from one state to the other, but is never in a simultaneous superposition of opposite magnetic moments.

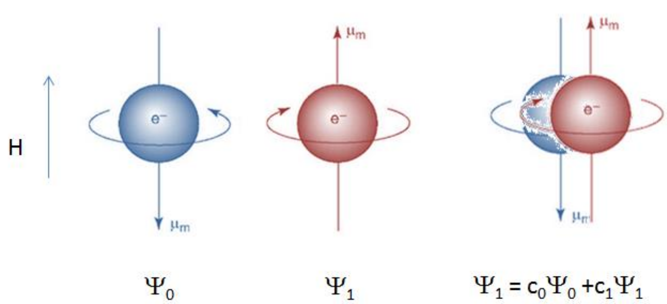


Fig. 1. Classical and quantum magnetic bits. A classical magnetic moment may align parallel or antiparallel to a magnetic field. In contrast, a quantum magnet such as an electron may also be in a superposition of up and down states (right), at least until its magnetism has been measured.

Quantum superposition is what turns a classical bit into a qubit, and is an essential requirement for quantum computing to have an advantage over classical computing. In classical computing, a logical operation is applied to one or more classical bits, generating output bits. In quantum computing, a logical operation is applied to one or more qubits, consisting of a linear transformation of the qubits, generating output qubits. Since the qubit is in a superposition state of $\Psi_0$ and $\Psi_1$, the logical operation on $\Psi$ is equivalent to operating in parallel on $\Psi_0$ and $\Psi_1$. In the case of classical bits, one must duplicate the hardware to achieve parallelism. For qubits, a single element has intrinsic parallelism following from quantum superposition.

This requires that the coherent superposition is maintained long enough for this logic operation to be completed, which may be microseconds or longer. A qubit may be subject to interaction with its environment, resulting effectively in a premature measurement that disrupts the coherence of the qubit. One form of environmental interaction consists of thermal fluctuations, both for particles on the microscopic level and for macroscopic electronic devices. For this reason, qubit systems are typically cooled down to very low temperatures.

But has quantum superposition in qubits really been observed? This suggests two distinct questions:

*1. Has quantum superposition been unambiguously demonstrated for macroscopic elements proposed for quantum computing?*

*2. Has quantum superposition been unambiguously demonstrated even for microscopic elements on the atomic level?*

We suggest that the answers to both questions may be NO, as discussed in more detail below. Furthermore, we suggest new experiments that may help to address these questions.

The magnetic moment of an electron corresponds to the magnetic field of a small current loop, which would also carry angular momentum. This permanent, intrinsic angular momentum is known as spin, and for the electron it has the value $S = \hbar/2 = h/4\pi$, where $h = 2\pi\hbar$ is Planck's constant.

Quantized spin is universal for all fundamental particles on the microscopic level. Another key example is the photon, the quantum of the electromagnetic field, with $S = \hbar$. A photon is uncharged, so that it has no magnetic moment. But the spin is associated with the polarization of the electromagnetic field. A linearly polarized EM field carries no angular momentum, while a circularly polarized EM wavepacket with spin $\hbar$ also carries energy $E = hf$, where f is the frequency of the wave [11,12]. Such a rotating EM field represents a real-space picture of a single photon, as shown in Fig. 2 (adapted from [13]). This field can rotate either clockwise or counter-clockwise, which corresponds to left circular polarization or right circular polarization (LCP or RCP), with opposite values of vector angular momentum.

The single photon is another standard two-state system in quantum mechanics, with the LCP and RCP states being $\Psi_0$

and $\Psi_1$. According to the standard quantum model, the indeterminate state of a single photon before measurement is given by Eq. (1), just as for a single electron. This is another example of a 2D Hilbert space. For example, if $c_0$ and $c_1$ are equal in amplitude, and the rotating fields are added in real space, the angular momentum in the resulting single-photon state would be zero, corresponding to linear polarization. So from this point of view, one could have a linearly polarized single photon, although quantum transitions with emission or absorption of photons correspond to $\Delta S = \pm\hbar$. The existence of such linearly polarized single photons is central to many prior experiments related to quantum information, and will be discussed in more detail below.

Quantum entanglement is a special form of quantum superposition that deals with systems of interacting quantum particles. There are two distinct types of quantum particles, known as fermions and bosons, as illustrated by electrons and photons, respectively. Electrons follow the Pauli exclusion principle, which states that two electrons in the same location cannot be in the same quantum state. So if electron A is in state $\Psi_0$, then electron B must be in state $\Psi_1$, or vice versa. Given quantum uncertainty, this is expressed as a linear combination of states $\Psi_0(A)\Psi_1(B)$ and $\Psi_1(A)\Psi_0(B)$. Specifically, the antisymmetric linear combination is used:

$$\Psi_{AB} = [\Psi_0(A)\Psi_1(B) - \Psi_1(A)\Psi_0(B)]/\sqrt{2} \qquad (2)$$

This has the property that the state changes sign when A and B are exchanged, which ensures that the Pauli exclusion principle is obeyed, and that electrons in the same quantum state repel each other. This antisymmetry property can be generalized to N electrons, so that the sign of the quantum state is reversed if any two particles are exchanged. Particles of this type have spin $S = (n+½)\hbar$ and are called "fermions".

In contrast, photons are not subject to the Pauli exclusion principle, and any number of photons can be in a given quantum state. The quantum state should remain unchanged if A and B are exchanged:

$$\Psi_{AB} = c_{00}\Psi_0(A)\Psi_0(B) + c_{01}\Psi_0(A)\Psi_0(B) + c_{01}\Psi_1(A)\Psi_0(B) + c_{11}\Psi_1(A)\Psi_1(B) \qquad (3)$$

This can be generalized to N photons, where the quantum state remains unchanged if any two photons are exchanged. Any particle with $S = n\hbar$, known as a boson, follows this behavior.

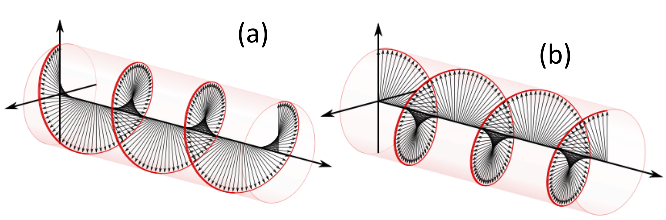


Fig. 2. Polarization states of a single photon. (a) Left circularly polarized photon, with spin $+\hbar$. (b) Right circularly polarized photon, with spin $-\hbar$. A linearly polarized photon may be regarded as a superposition of (a) and (b) in real space. Images adapted from [13].

In the case of either fermions or bosons, the two particles are intrinsically entangled, in a way that is incompatible with local realism. For example, consider two electrons that are initially in a coupled state, which therefore must have opposite spins. If they subsequently move apart, they will remain anti-correlated, even as the individual electron spins are undetermined. Furthermore, a measurement on one of the two coupled electrons will immediately affect the state of the other electron, no matter how far apart they have moved. This aspect troubled Einstein, who called it "spooky action-at-a-distance". He presented a thought-experiment (known as the EPR Paradox, [14]), which was unresolved for many years. However, experiments on coupled photons starting in the 1970s reported agreement with the predictions of quantum entanglement [15], leading most physicists to believe that nonlocal quantum entanglement is an unavoidable aspect of nature. We question the interpretation of these experiments, as discussed below.

A qubit is any quantum system, microscopic or macroscopic, that can be expressed as a superposition of two quantum states, as in Eq. (1). To make a quantum computer, two or more of these qubits must be coupled together to form a quantum logic gate or computing element, and will generally exhibit entanglement. The entanglement of a macroscopic state seems paradoxical, and indeed this paradox was identified quite early by Schrödinger, in his famous "Cat Paradox" [16], where a cat could be in a superposition of being living and dead. Although this was proposed to point out shortcomings of the theory, Schrödinger cat states are now generally believed to represent real physical objects with undetermined physical properties.

As shown in Eq. (3), two entangled qubits can provide a superposition of 4 qubit configurations. More generally, N entangled qubits have $2^N$ states evolving in parallel, equivalent to an exponential expansion of the Hilbert space in which the quantum state operates. The degree of parallelism increases exponentially with the linear rise of hardware, which is why the promises of quantum computing are so revolutionary. A variety of physical systems have been proposed for quantum computing [17]. These include electronic and nuclear spins, trapped gaseous atoms or ions, quantum dots, and superconducting circuits. We focus on superconducting circuits based on Josephson junctions, which show promise of integrated circuit scaling to large numbers of qubits.

## III. Superconducting Quantum Computing

Superconducting devices and circuits are already being used for classical computing, and similar elements (Josephson junctions connected with superconducting wires) are being developed for quantum computing. A superconducting wire is an ideal lossless inductor L, so that from Faraday's Law ($V = d\Phi/dt$) the magnetic flux $\Phi$=LI in a closed superconducting loop must be conserved. Further, from the quantum nature of the superconducting state, $\Phi = n\Phi_0$, where $\Phi_0 = nh/2e = 2.07 \times 10^{-15}$ Wb is the magnetic flux quantum.

A Josephson junction is the active element in superconducting circuits, and consists of two superconductors separated by an ultra-thin (~1nm) insulating layer, through which a small lossless current (the critical current $I_c$, typically on the μA scale) can pass as a quantum tunneling current. In its superconducting state, a Josephson junction consists of a parallel combination of a (nonlinear) inductor and a capacitor, i.e., it is a high-Q LC resonator, with a resonant frequency typically in the microwave range. A Josephson junction may also include loss modeled by a temperature-dependent resistor, but in ideal junctions the loss becomes exponentially small as T goes to zero.

In addition, for a current greater than $I_c$, a Josephson junction acts as a switch, which can transfer a single flux quantum (SFQ) across the junction. This is equivalent to generating an SFQ voltage pulse, with integrated voltage $\int V dt = \Phi_0 = 2$ mV-ps (typically ~ 1 mV high and 2 ps wide). Such a pulse can be transmitted to another junction, where it can trigger a similar switching event. This enables classical logic gates.

A superconducting loop containing one or two Josephson junctions is known as a Superconducting Quantum Interference Device, or SQUID. A SQUID can be configured so that there are only 2 stable states, with different circulating currents. Because the SQUID is bistable, it can operate as a memory bit or latch, provided that thermal fluctuations cannot switch the bit, but deliberate SFQ pulses can do so. Further, a switched bit generates another SFQ pulse, which can propagate down a superconducting line and trigger another SQUID latch or gate.

These logic and memory circuits provide the basis for Rapid Single Flux Quantum (RSFQ) logic, which is the most common logic design for superconducting classical computers. Fig. 3 shows a conceptual diagram of an RSFQ flip-flop circuit containing Josephson junctions and SQUIDs, from [6]. These circuits are generally synchronous digital circuits that operate at a clock rate up to 100 GHz, also provided by SFQ pulses. Ironically, Josephson junctions in RSFQ circuits typically have shunt resistors deliberately added to make the junction resonators critically damped. An underdamped junction will ring, which is undesirable for a fast digital logic circuit. Even so, circuits based on SFQ logic families are among the lowest power and fastest in any computer technology [18].

But just because SFQ and SQUID contain the word "quantum", this does not imply that they are operating as true quantum elements. A SQUID can be represented by the double-well potential energy plot of Fig. 4. As a classical circuit element, a SQUID operates at one of the minimum points of the potential wells, or oscillating around one of these minima due to thermal fluctuations, or transitioning from one to the other as driven by a pulse. In contrast, we can think of the same SQUID as a quantum device at T=0. Here, one has quantized energy levels in each well, and a device in one of these states is not in a fixed position, but rather is distributed, with tails that penetrate the barrier as shown in Fig. 4. This is much like the case of an electron in a potential well, and it is well known that an electron has a distributed wave function. Of course, the SQUID is not a single electron, but rather a macroscopic electronic device with millions of electrons. If the SQUID acts similarly to an electron, these are known as "macroscopic quantum effects", in analogy with microscopic quantum effects that apply to single-electron states.

One important microscopic quantum effect is quantum tunneling. This occurs, for example, with an electron in a metallic layer, with a potential barrier that would normally prevent the electron from escaping the layer. For high T, it may be possible for classical thermal fluctuations to excite the electron over the potential barrier. At ultra-low T, the electron may still "tunnel through" the barrier due to its distributed wave function. Specifically, the exponential tail that penetrates the barrier leads to a small but significant statistical probability that the electron will find itself on the other side of the barrier. Electron tunneling is well established for barriers on the nm scale, and is responsible for the current in Josephson junctions.

The analogous behavior for the bistable SQUID bit (or any other bit for that matter) would be for the bit to switch from one state to the other, at a temperature too low for that to occur via thermal excitation. This effect is known as macroscopic quantum tunneling (MQT). There are many experiments on Josephson junctions and SQUIDs at very low temperatures (well below 1 K) that have been explained using the theory of MQT [19,20], but see the discussion below.

Another microscopic quantum effect is when an electron wave function may be distributed over both wells at the same time. This may occur if the barrier height is relatively shallow, or the width relatively small. In that case, the total electron wave function may be written as a linear superposition of those on the two sides, as in Eq. (1). There

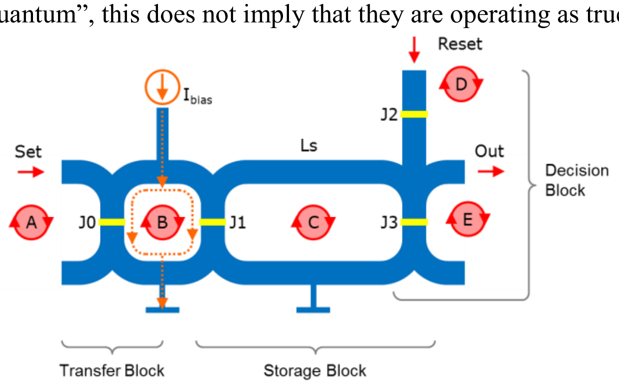


Fig. 3. Schematic of flip-flop in Rapid-single-flux-quantum (RSFQ) logic, a classical computing system using Josephson junctions and SFQ voltage pulses (figure from [6]).

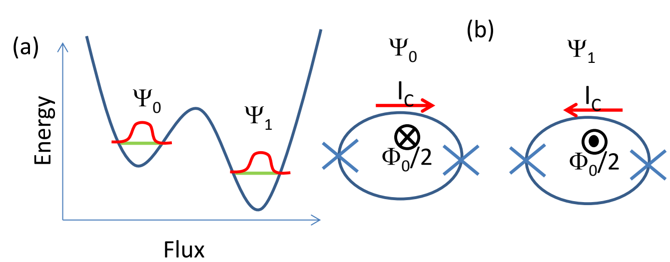


Fig. 4. SQUID as Flux Qubit. (a) Double-well potential energy of bistable SQUID, showing quantized energy levels and distributed quantum waves. (b) Configurations of currents in two classical states, which may be combined in superpositions for the flux qubit.

may also be two total electron wave functions (with different energies), for example a symmetric and an antisymmetric combination, similar to that in Eq. (2).

The same thing is believed to be the case for a SQUID at ultra-low temperatures, which would provide an example for "macroscopic quantum coherence" (MQC). In general, the requirements for MQC are believed to be somewhat more stringent that those for MQT, so that lower temperatures and reduced environmental interference (longer coherence times) may be necessary. Measurements on superconducting qubits were interpreted as supporting the predictions of MQC [21, 22], including superposition and resonant transitions between quantized energy levels (known as Rabi oscillations). The other requirement for quantum computing is the existence of quantum entanglement between multiple qubits, and recent experiments on superconducting qubits have found results consistent with entanglement theory [23]. However, some remain skeptical of all these analyses [7], as discussed below.

The qubit version of the SQUID is known as a "flux qubit. There are also other types of superconducting qubits that have been developed [4], such as a "charge qubit", based on small superconducting capacitor where transfer of a single electron changes the energy level, and a "phase qubit" based on energy levels in a single Josephson junction. In all cases, it is believed that the qubit may be in a quantum superposition of the two states defining the bit.

Apart from the types of qubits, there are several distinct architectures that have been proposed for quantum computing using superconductors. The ultimate quantum computer would comprise a universal digital computer with large numbers of entangled qubits, digital gates, and quantum error correction [8]. Nothing like this is presently available, or is likely in the near future. This is the type of computer that is projected for applications such as efficient factoring of large integers (Shor's algorithm) for cryptography. In contrast, there are several proposals for analog computing, where an array of superconducting qubits simulates another quantum system. Some of these approaches fall under the rubric of "adiabatic quantum computing", which may be somewhat more tolerant of thermal fluctuations than the universal digital quantum computer. One specific approach that has led to a commercial superconducting computing system is quantum annealing [5].

Quantum annealing is based on a classical computing method known as simulated annealing [24], which in turn is based on the physical concept of atomic crystallization. An ideal crystal consists of a regular array of atoms, but all real crystals have some defects – atoms missing or in the wrong positions. These defects are high-energy configurations, but they may be metastable, requiring excitation over a potential barrier for the defect to be "repaired". If one heats the crystal near the melting temperature, and cools it down slowly, this process of crystalline annealing may permit the defects to be removed. But it is likely that some defects will remain, and one may need to carry this thermal cycling multiple times to get as close as possible to the ideal perfect crystal. An alternative path toward the ground state may consist of quantum annealing, which corresponds to quantum tunneling of the atoms, which may permit a faster approach to the ideal ground state, even at low temperatures. Such an algorithm (either the classical or quantum version) can be run on a general purpose digital computer, but in some cases, an analog simulator consisting of simulated atoms with simulated nearest-neighbor interactions may be much faster or more flexible, particularly for large crystal sizes.

This might seem to represent a specialized computer with a very narrow market, but in fact there are a wide range of optimization problems that can be solved in this way, particularly if states of the individual atoms may be programmed [25]. The primary model system for these analog computers is known as the Ising Model, and corresponds to a regular two-dimensional array of atomic magnets, each of which can point either up or down (Fig. 5a). The nearest neighbors try to line up with each other, but the initial conditions of the atoms are in general in different directions, and the path to the optimum ground state may be frustrated and inefficient.

D-Wave Systems, Inc. (http://dwavesys.com) has recently developed an analog quantum computer [5,26] based on a 2D array of superconducting flux qubits (bistable SQUIDs), each of which can classically be in either of two states, with nearest-neighbor qubits inductively coupled to one another (Fig. 5b). The initial conditions of each of these SQUIDs can be externally programmed. This represents an analog simulator for the 2D Ising model, which may function as a thermal annealer or a quantum annealer, depending on the temperature. It is designed to operate down to 20 mK, where quantum effects are believed to be dominant. Systems with up to 1000 flux qubits have been tested, and appear to be working properly. The key question is whether these results indicate that the system is operating as a classical thermal annealer, or shows some degree of accelerated performance due to macroscopic quantum tunneling. A related question is whether these results indicate the presence of quantum entanglement in clusters of flux qubits. Although previously there was considerable skepticism among parts of the of the quantum computing community over whether the D-Wave Processor really exhibited quantum speedup, more recent evidence by several research groups has tended to be supportive [27].

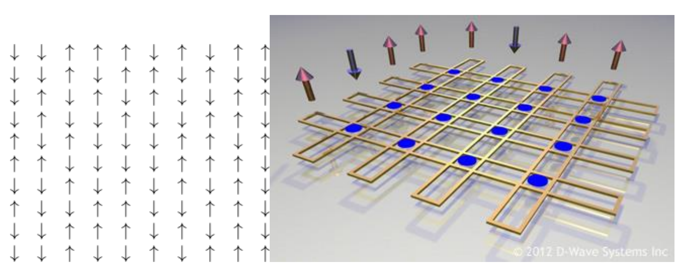


Fig. 5. Analog Simulated Annealing Processor. Left, 2D Ising Model, consisting of array of coupled atomic spins. Right, array of inductively coupled SQUIDs, functioning as flux qubits, designed to map onto spins in the Ising Model (figure from [28]). At sufficiently low temperature, an annealing processor is expected to cross over from thermal annealing to quantum annealing.

Finally, we emphasize that despite the consensus in favor of the possibility of superconducting quantum computing, there is an important minority opinion that questions whether the experiments have been properly interpreted in terms of quantum superposition and entanglement. For example, simulations using purely classical Josephson junctions and SQUIDs have quantitatively fit observations that were previously modeled as MQT and MQC [7,29,30]. With respect to MQT, an increase in effective temperature, due to noise-induced heating or semi-classical zero-point oscillations, can explain many of the results. MQC features that had been uniquely associated with quantum effects of Rabi oscillations, Ramsey fringes, and spin-echo were given quantitative classical explanations based on resonant transitions between states of coupled classical nonlinear oscillators (such as Josephson junctions) [29]. Even observations of entanglement in coupled Josephson qubits [23] may have a classical explanation [30]. Taken together, this suggests that the experimental evidence on *macroscopic* superposition and entanglement may be much less robust than many in the computing and physics communities have been led to believe. Without such entanglement, the promised benefits may be illusory. In the next section, we question whether these effects have been demonstrated even on the *microscopic* scale.

## IV. Quantum Realism and Proposed New Experiments

In this section, we present several new experiments that will address the issues of quantum superposition on the microscopic and macroscopic levels. These are motivated by an alternative realistic quantum picture with quantized energy levels, but without uncertainty, superposition, or entanglement [31,32]. This alternative picture matches some predictions of standard quantum mechanics, but not others. The proposed experiments should be straightforward using modern instrumentation, and may provide clear evidence on whether qubits based on quantum superposition are really possible. Given the large present and future investment in quantum computing, such proposed experiments are too important to overlook.

We present here a brief outline of this alternative quantum picture. All "elementary particles" are distributed rotating vector fields which carry both angular momentum and energy. There are no point particles, and composite particles are simply bags of confined wave packets. This is motivated by the realistic picture of a single photon in Fig. 2, as a circularly polarized electromagnetic wave with quantized spin $\hbar$. Similarly, an electron is a soliton-like de Broglie wave packet with quantized spin $\hbar/2$ (see Fig. 6), with rotational frequency in its rest frame is $f=mc^2/h$, and the wave transforms relativistically. The Pauli exclusion principle is a consequence of the properties of the electron self-field, rather than the entangled mathematical construction of Eq. (2). Within this picture, quantum mechanics is just a mechanism to obtain discrete particle-like behavior from continuous fields. Quantized energy levels and angular momentum at higher levels follow from microscopic spin quantization. For example, vibrating atoms follow classical oscillations at frequency f, but only discrete amplitudes corresponding to $E = (n+½)\,hf$ are accessible.

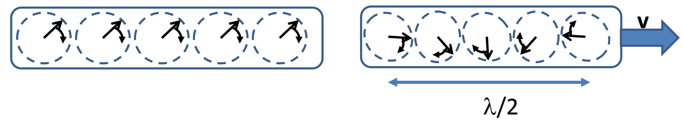


Fig. 6. Alternative realistic quantum picture of single electron as distributed coherently rotating vector field carrying quantized total spin. Left, electron at rest; right, moving electron transforms as de Broglie wave. No point particles, statistical indeterminacy, superposition, or entanglement are present in the model.

How would experiments on electron spin and photon polarization, the two quantum examples presented earlier, be viewed within this alternative realistic quantum picture? Consider first the classic Stern-Gerlach (SG) experiment [33] from 1922, where a beam of neutral univalent atoms (Ag) was directed into a non-uniform magnetic field. The beam was found to split into two discrete sub-beams, as opposed to the continuous distribution that would be expected from classical physics. This provided the earliest experimental evidence of quantization of spin. The SG experiment may be easily understood if one assumes that the atoms are in a mixture of spin-up and spin-down states, as shown in Fig. 7a. The gradient in magnetic field simply provides magnetic separation of these two populations. This explanation contrasts with orthodox quantum theory, in which the initial state of the atoms is an indefinite linear superposition of spin-up and spin-down states, as in Eq. (1). The experiment constitutes a quantum measurement that forces a given electron into one or the other of these states, which are then separated in the gradient. This yields the same split-beam result as the argument above.

However, these two alternative approaches predict quite different results for the two-stage SG experiment shown in Fig. 7b. This two-stage SG experiment is a standard paradigm for quantum measurement, and is widely used in quantum mechanics texts (including the Feynman Lectures [34]), but this has apparently never been tested (as Feynman admitted). The second stage is the same as the first, but rotated by an angle θ. Within the realistic picture, the spins in the excited state (labeled + in the figure) will follow the fringe fields and rotate coherently into the excited state of the second magnet, yielding 100% in Detector 1 and 0% in Detector 2. In contrast, the orthodox quantum theory states that the excited-state spins will project onto a rotated spin basis in the 2nd polarizer, yielding a statistical average $\cos^2\theta$ in Detector 1 and $\sin^2\theta$ in Detector 2. This latter prediction is so widely believed that there is an online Flash Animation that incorporates it [35]. This experiment should be straightforward to do using modern

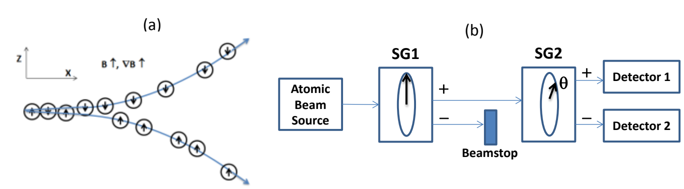


Fig. 7. Stern-Gerlach experiments using magnetic fields to separate atomic beam components of different spin. (a) Mixed beam of spin-up and spin-down atoms separated by inhomogeneous field. (b) Block diagram of two-stage Stern-Gerlach experiment to test for spin superposition. This standard textbook thought-experiment has never actually been carried out.

atomic-beam equipment, which would provide a definitive test of spin superposition.

One reason that the $\cos^2\theta$ dependence for the double SG experiment is widely believed, without direct experimental verification, may be that this is the same prediction as for the well-known crossed-polarizer experiment with light in the classical limit, using two linear polarizers with an angle $\theta$ between them. On the quantum level, the spin and polarization problems are both two-dimensional Hilbert spaces, and are believed to behave identically. But we have already suggested that within the realistic picture, electron spins will be a *mixture* of spin up and spin down, rather than a superposition. How would this picture affect single photons?

If we assume that quantization of spin is central to a realistic picture of a photon, then a single photon must always be circularly polarized. One can certainly generate linearly polarized classical fields by taking the superposition in real space (rather than in Hilbert space) of circularly polarized photons of opposite helicity. However, it is widely believed that linearly polarized single photons were measured long ago, by detecting single photons passing through a linear polarizer. In fact, measurements on linearly polarized single photons are central to most of the experimental demonstrations of quantum entanglement [15]. So can we really question the existence of these linearly polarized single photons?

First, most conventional photon detectors, such as avalanche photodiodes or photomultipliers, are really event detectors [36]. They cannot distinguish one photon from two photons absorbed at the same time. So it is conceivable that photons passing through linear polarizers may be matched photon pairs, rather than single photons. An energy-sensitive photon detector with very high quantum efficiency could directly measure both photons. Fortunately, such detectors now exist, based on superconducting single-photon detectors. Recent experiments using these detectors have measured the attenuated output of a pulsed laser as consisting of a small number of photons (0, 1, 2, 3…) [37,38]. We propose doing a similar experiment, but inserting a linear polarizer before the detector [10]. As Fig. 8 suggests, if this eliminates the odd peaks, that would suggest that linearly polarized photons are actually pairs. If this were found to be true, this would require that the interpretations of many experiments in quantum optics and quantum communication would need to be reevaluated. In particular, the experiments claiming support for quantum entanglement and nonlocality would come into question.

Finally, let us consider a possible test of superposition in superconducting flux qubits [9]. In the classical case, this is a SQUID latch that can undergo transitions between the two states, associated with an SFQ pulse transferred into or out of the SQUID. Can we similarly monitor the flux state of a flux qubit, at the same time as we monitor its energy? Within the orthodox quantum theory, a flux qubit may be placed in a quantized energy state (energy eigenstate) that is in a superposition of flux states, so that the flux is not definite. In such a situation, the circulating current would not be definite either; it would be in a superposition of current flowing in opposite directions. This is contrary to local realism.

A possible way to obtain a direct measurement without destroying quantum coherence is indicated in Fig. 9 [9]. The output flux is coupled to the input SQUID of a Josephson transmission line (JTL), which propagates an SFQ pulse down the line. The junctions in the JTL are always in the zero-voltage state, except during the ~1 ps when an SFQ pulse is generated. This should generate very little back-action on the qubit. Furthermore, the coupling parameters may be designed so that the damping effect of the nearest JTL junction may be minimized. The general concept of using SFQ circuits to read out a flux qubit was described some years ago by Feldman and Bocko [39,40], but apparently not fully realized. It may be time to reconsider such an SFQ approach, using modern high quality Josephson junctions and circuits.

## V. Discussion and Conclusions

The foundations of quantum mechanics were the subject of much early controversy, and these debates were never quite resolved. For many decades, the predominant view was that these were philosophical issues, with no real practical implications. With the promise of quantum computing, however, there are potentially major technologies that are critically dependent on the very quantum paradoxes that physicists were debating 80 years ago. It is generally believed that the relevant experiments have already been done, and show clearly that quantum superposition and entanglement are real. But an experiment can never prove a theory to be correct; it can only demonstrate consistency. If experiments on Josephson junctions can be quantitatively explained by classical analyses, that would bring into question macroscopic qubits. Furthermore, we have identified some experiments on electrons and photons that have evidently not been carried out, but should be straightforward using modern laboratory equipment. If the Hilbert-space formalism is found not to apply to electrons and photons, its applicability elsewhere would be in jeopardy. Entanglement could lead to the demise of orthodox quantum theory, rather than becoming its greatest success.

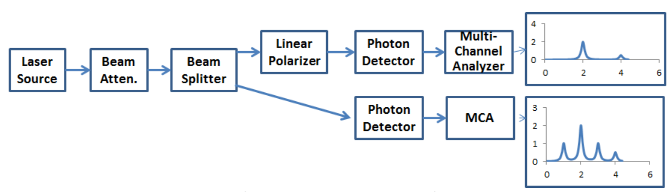


Fig. 8. Block diagram of experiment to test for linearly polarized single photons. New superconducting photon detectors have high quantum efficiency and energy resolution.

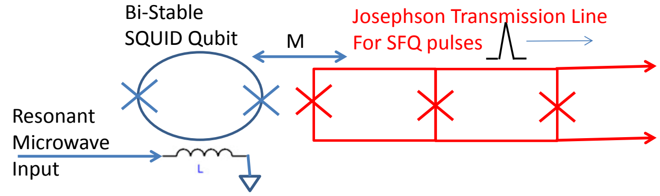


Fig. 9. Block diagram of experiment to test for superposition in flux qubit. Flux changes in the loop can be measured by observing SFQ pulses coupled out, while avoiding environmental loading and noise.

Without entanglement, would there be anything left to quantum computing? We suggest that analog quantum simulations of the type represented by quantum annealing may be the only practical developments from this field, since they do not seem to require multi-qubit quantum entanglement. This is not to minimize their significance for a wide range of quantum dynamics and optimization problems. However, they would not provide the truly massive parallelism promised by the entanglement approaches, and they would not put classical digital computers out of business.

Finally, if it were found that local realism applies down to the microscopic level, that would not signal the end of ambitious future computing schemes. On the contrary, it would suggest that classical bits could be scaled all the way down to the atomic level, provided that thermal and environmental noise can be minimized. As Feynman noted in 1959, "There's (still) plenty of room at the bottom" [41].

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