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An Investigation of the Role of the Effectiveness of Different kinds of Qubits in Quantum Computing

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***Abstract*—Quantum computers are envisioned as the computers of the future. The principles of physics that govern the subatomic realm, where constituent particles can exist in several states and locations at once, serve as its foundation. The technique uses a quantum computing paradigm to take advantage of the behavior patterns of matter and energy at the quantum level. They offer quantum effects to deliver solutions for incredibly complex problems that cannot be resolved by regular computers in a reasonable length of time. Modern quantum computers frequently have a limited number of qubits. Their tendency to make mistakes is their main problem. The more complex a system is, the harder it is to entirely isolate it from its surroundings. One approach is to use topological qubits, which encode information according to their spatial arrangement. Topological qubits are believed to be extremely resilient to decoherence from the outside and to be exceptionally durable. They appear to be able to switch swiftly and are comparable to the conventional superconducting qubits used by Google and IBM in contemporary quantum computers. One approach is to use topological qubits, which encode information according to their spatial arrangement. Majorana zero modes (MZMs), which are non-Abelian anyons, have the potential to provide topologically secure quantum computation. With quantum information stored in the spin or charge states of constrained electrons, quantum dots are small semiconductor structures that can function as qubits. A transmon is a specific kind of superconducting charge qubit used in superconducting quantum computing that was created to have less susceptibility to charge noise. This review paper analyzes three kinds of qubits that are effective for quantum computing and differ from the normal kinds of qubits such as superconducting and photonic qubits**

Keywords*— Transmons, Quantum Computing, Topological Qubits, Majorana Zero Modes, Anyons, Photonic Qubits, Superconducting Qubits.

I. INTRODUCTION

Numerous industries, like protein folding simulation and cryptography, stand to benefit greatly from quantum computing. The optimum physical framework for constructing the underlying quantum bits is still up for debate. These so-called qubits, in contrast to the conventional bits in your computer, may accept not only the values 0 and 1, but also combinations of the two. They become extremely unstable while yet having the potential to be incredibly valuable. Future computers are thought to be quantum computers. They offer solutions for extremely complicated issues that can't be solved by ordinary computers in a reasonable amount of time using quantum effects. However, it will be a while before these computers are used widely. There are often not many qubits in modern quantum computers. The fundamental issue is that they are quite error-prone. It becomes increasingly challenging to completely isolate a system from its environment the larger the system gets. Topological qubits that encode the information in their spatial arrangement are one strategy for solving this problem. That might offer a framework for computing that is more reliable and resistant to errors than previous arrangements. As a result, topological qubits are thought to be highly durable and substantially resistant to outside sources of decoherence. Additionally, they seem to be able to switch quickly, matching the traditional superconducting qubits employed by Google and IBM in modern quantum processors. The issue is that no topological qubit has ever been definitively discovered. A group of researchers in Austria have examined a setup for the majorana zero modes which are a crucial ingredient to the topological qubit. They also discovered that a true signal for these modes can occasionally be a misleading one. Non-Abelian anyons known as Majorana zero modes (MZMs) show potential for enabling topologically protected quantum computation. They can appear near the termination of 1D topological superconductors as localized zero-energy states.According to the scientists' beliefs, the Majorana zero modes, which form the foundation of the topological qubit they were looking for, should manifest themselves in the nanowire. Because they were first used as a mathematical ruse to depict one electron in the wire as being made up of two halves, these Majorana zero modes are a peculiar occurrence. In contrast to how most physicists perceive electrons, this nanowire configuration should have made it possible to extract these "half-electrons" and use them as qubits. The culprit was discovered after the uncoated junction's length was doubled to 200 nanometers. The following occurred when the junction was sufficiently large: A "quantum dot," or small particle of matter with unique quantum mechanical features because of its constrained geometry, was created by the exposed inner nanowire. The electrons in this quantum dot might then interact with those in the superconductor coating adjacent to it, simulating the signal of the "half-electrons' ' (the Majorana zero modes), which are electrons with no magnetic field.

II. QUANTUM DOT QUBIT

The development of qubits in semiconductor quantum dots, using one, two, and three quantum dots to host qubits, has advanced significantly. One benefit of employing two or more quantum dots to host a single qubit is the ability to operate at sweet spots, a method invented for superconducting qubits that makes the qubit more resistant to charge noise. Charge noise is frequently the main cause of decoherence in semiconductor qubits.The techniques of handling and sending information in quantum computation and quantum communication have been greatly enhanced by quantum information processing, which is based on quantum mechanics theory. Parallel quantum computation, which is theoretically considerably quicker than traditional processing, offers a revolutionary method for accurately controlling and manipulating the states of quantum systems. A crucial component of quantum computation is the quantum logic gate. Finding a practical physical implementation for quantum logic gates is crucial. Many proposals have been made to implement controlled-not (CNOT) gates or controlled phase-flip (CPF) gates in both theory and experiment using a variety of quantum systems, including the ion trap, free electron, cavity-QED system, nuclear magnetic resonance, quantum dot, superconducting charge qubits, and the polarization states of single photons. Physical systems must meet certain criteria in order to create a quantum computer, including scalability, effective manipulation, reading out the state of a single qubit, strong coupling between qubits, and weak coupling to the environment. With its excellent optical properties and scalability, a solid-state quantum system based on an electron spin in a quantum dot (QD) inside a microcavity (QD-cavity) recently gained a lot of interest. Numerous quantum information operations, including entanglement creation, Bell-state analysis, quantum gates, hyper-entangled Bell-state analysis, and quantum repeater, may be implemented using the optical feature of QD-cavity systems. In quantum network theory, it is widely known that every universal quantum computing may be realized using two-qubit gates and one-qubit rotations. The sheer number of element gates in quantum logic circuits, the implementation of element gates, and other issues must be addressed in order to put theory and technology into practice. The creation of CNOT gates and CPF gates that operate on a single degree of freedom (DOF) of quantum systems, such as the polarization DOF of photon systems or the spin DOF of electron systems, has so far yielded several significant studies. Assisting in the development of quantum logic gates that operate on the polarization (spatial-mode) DOF, the spatial-mode (polarization) DOF of photon systems is often employed, and the spatial-mode (polarization) DOF is consumed after the operation. On two DOFs of quantum systems, the spatial-mode and polarization DOFs of photon systems can both be utilized as qubits for universal quantum gates. The current hyper-CNOT gate is made using a double-sided QD-cavity system with partly reflecting mirrors, which exhibits the optical reflection/transmission geometry feature. The substantial reflectance and transmittance difference between the connected cavity and the uncoupled cavity makes the hyper-CNOT gate durable and adaptable25. Additionally, the issue of how to fit the many spatial modes of a photon into the single-sided cavity must be resolved in the one-side QD-cavity technique. Due to the fact that a double-sided cavity has two balanced spatial modes, this does not present an issue for this technique. Additionally, in this double-sided QD-cavity protocol, the operations on the two spatial modes are merged, notably for the Mach-Zehnder interferometer caused by the CPBSs. That is, the current hyper-CNOT gate has a better fidelity and efficiency than the one used in the one-side QD-cavity protocol. The hyper-CNOT gate operation enables the implementation of quantum information processing with less photon resources, which can lower the resource requirements for the construction of quantum logic circuits and the storing of data. Additionally, in the quantum information processing based on two DOFs of photon systems, the photonic dissipation and the ambient noise impact are suppressed. Additionally, combining two DOFs of photon systems reduces photon interaction durations in quantum information protocols as compared to integrating multiple cascaded CNOT gates into a single DOF. One might theoretically build a hyper-parallel photonic quantum processor using the current hyper-CNOT gate and single-photon quantum gates, and one could also easily prepare and analyse multi-photon hyperentangled states. In theory, additional quantum systems with nonlinear optics, including Rydberg atoms, cross-Kerr media, nitrogen-vacancy centers, and wave-guide nanocavities, can also be utilized to implement scalable hyper-parallel quantum processing. Here, the two photons with two DOFs are employed as four qubits, and the hyper-CNOT gate operation is used to operate on the polarization and the spatial-mode DOFs separately. In reality, the two photons with two DOFs may also be employed as two qudits in the processing of quantum information. Additionally, because the single-qubit gates for the two DOFs of a photon can be implemented independently and the CNOT gate on the two DOFs of a photon can be easily implemented with linear optical elements, the multi qubit hybrid logic gate can be implemented more easily and with fewer photon resources by using the two DOFs of the photon system. In order to accomplish the CNOT gate operations without employing the auxiliary spatial modes, the two DOFs of a two-photon system are employed in the building of the hyper-CNOT gate. This method is more easier than the one that uses quantum dots within one-side optical microcavities. Therefore, whether or not individuals employ the measurement of electron spins depends on the experimental method.

III. TRANSMON QUBITS

In SQC with transmons, there have been a number of innovations, from the understanding of quantum supremacy to quantum chemical simulations. An artificial quantum system called a superconducting qubit has a macroscopic scale, or a dimension that typically ranges from 300 to 500 micrometers. One of the disadvantages of SQC is that it has a very short coherence period when compared to other natural candidates for the quantum computer, such as trapped ions, cold atoms, and NV centers. As a result, since the invention of superconducting qubits at the turn of the 20th century, there has been a protracted struggle to increase their coherence time. The coherence time has improved by more than 5 orders of magnitude up to this point, but there is still much more progress to be made. Although one can achieve lifetimes for superconducting qubits of tens or even hundreds of microseconds utilizing cutting-edge transmon design and fabrications, it is still unable to match the specifications of a realistic SQC system, particularly for the error threshold of quantum error correction. The main constraints for effective quantum processing and quantum simulation are improved gate fidelity and wider circuit depth, which are possible benefits of longer coherence time. Charge noise and flux noise are reduced for a fixed frequency transmon qubit, and the sapphire substrate's dielectric loss is anticipated to be more than 10 ms. The two-level system (TLS) defects in the material interface are the main cause of decoherence22. These defects occur at the metal-substrate (MS), metal-metal (MM), and metal-air (MA) interfaces between Nb (Al or Ta) films and the substrates, Al Junction films, and air, respectively. In our devices, the sapphire substrates were treated delicately through chemical cleaning and annealing. It was heated in a load-lock chamber for degassing at 200 °C for two hours prior to film deposition. The control and measurement wires for our single qubit circuit were heavily attenuated and filtered; however, this cannot be done for a multi-qubit semiconductor since we need to regulate and bias the qubits rapidly enough. Decoherence is the outcome of this, which sends high-frequency disturbances via the wires to the qubits. Therefore, to increase the coherence time of large-scale quantum circuits, the measurement system's external noise should be properly controlled. At this time, this is a difficult problem. To get a longer coherence time. First, a single-junction fixed-frequency transmon design was chosen because it significantly lessens the impact of flux noise. In order to reduce environmental noise, the circuit is further simplified to just require the two electrodes for the feedline and does not have delicate control lines for individual qubits. Five transmons make up the circuit; each is dispersively linked to a readout resonator before being connected to a transmission line acting as the feedline. As a result, the transmission line's one port serves as the input for both the microwave driving pulses and readout pulses. To lower the electric field density and the effects of surface loss, each qubit includes a shunted capacitor with a larger pad area, following the design of the Princeton and IBM groups.

IV. TOPOLOGICAL QUBITS

The subject of quantum error correction and fault-tolerant computation is a suitable location for topological ideas. Topology is concerned with an object's "global" characteristics, which are unaffected by local deformation. Quantum error correction's main goal is to manipulate and store quantum information in a "global" form that is impervious to local perturbations. In order for the action it takes on the encoded data to stay intact even if we slightly distort the gate—that is, even if the implementation of the gate is imperfect—fault-tolerant gates should be created to act on this global information. When Hilbert space is partitioned into mutually orthogonal sectors, each of which is preserved by any local operation (in a field theory or spin system specified in an unlimited spatial volume), a superselection rule, as we use the term here, emerges. The charge superselection rule in quantum electrodynamics is arguably the most well-known example. An electrical charge has an indefinite range. A charge cannot be created or destroyed locally since doing so would require destroying the electric field lines that extend into the entire community, which is impossible to do locally. The Aharonov-Bohm interaction is likewise an infinite range effect; regardless of the electron's distance from the solenoid, it enters an Aharonov-Bohm phase as it circles the solenoid. Consequently, we may conclude that no local operation can destroy a charge involved in the Aharonov–Bohm phenomenon. Any process that modifies the charge on either item would have to function coherently over the whole region holding the two charges if we imagine two things carrying such charges that are widely separated from one another and well isolated from other charged objects. Therefore, even in the presence of small disturbances, the charges are rather durable; we may hit the particle with a hammer or otherwise abuse it without changing the charges it carries. A topological quantum computer is a hypothetical device in which quantum information is encoded in the quantum numbers carried by quasiparticles that exist on a two-dimensional surface and interact with one another across vast distances using the Aharonov-Bohm principle. Only the quantum tunneling phenomenon, which involves the virtual exchange of charged objects, may result in an error, or inadvertent exchange of quantum numbers between quasiparticles, at absolute zero. Our device's Aharonov-Bohm phenomenon must be nonabelian in order for it to be able to execute intriguing calculations. Only then will we be able to sequentially undertake several particle exchanges to create sophisticated unitary transformations. Systems with non abelian gauge fields may experience such non abelian Aharonov-Bohm effects. Unfortunately, there aren't many basic non abelian gauge fields that nature has given us, and none of them appear to be suitable for actual quantum processing. We must thus expect that non abelian Aharonov-Bohm effects can manifest as intricate collective phenomena in (two-dimensional electron or spin) systems with only short-range fundamental interaction in order to realize Kitaev's goal. In fact, the detection of the fractional quantum Hall effect led to one of the most amazing discoveries of recent decades: finite range Aharonov-Bohm events may occur in such systems. In quantum Hall systems, the electrons are so intensely frustrated that the ground state is incredibly entangled, with powerful quantum correlations spreading out across considerable distances. Therefore, the electron wave function gains a nontrivial Berry phase when one quasiparticle is carried around another, even if the quasiparticles are widely apart. The experimental results of this Berry phase, which is identical in all of its observable effects to an Aharonov-Bohm phase resulting from a fundamental gauge field, are astounding. Although there is some strong evidence that non abelian Berry phases can exist under the correct circumstances, the Berry phases seen in quantum Hall systems are abelian, making them uninteresting from the perspective of quantum processing. There are two different nonperturbative effects that might occur. The theory's ground state might transform into a flux condensate, which would have an infinite number of magnetic excitations. In this scenario, charged particles and their antiparticles would interact attractively across a great distance. There wouldn't be any long-range impacts, and it would be hard to separate the charges. This phenomenon would be known as electric confinement in a gauge theory. Alternatively, the ground state could exhibit a condensate of electric quasiparticles. Following the confinement of the magnetic excitations, the long-range Aharonov–Bohm effects would once more be eliminated. This is known as the Higgs phenomenon (or magnetic confinement) in a gauge theory. We may predict that Kitaev's Hamiltonian will ultimately reach a phase barrier, beyond which either electric condensation or the Higgs phenomena will take place. How exactly a material must be created in order to function as a Kitaev species will depend on how large the area that this border encloses. If skillfully selected two-body interactions may frustrate a spin system enough to create a highly entangled ground state and nonabelian Aharonov-Bohm interactions among the quasiparticle excitations, that poses a particularly pressing dilemma for the material designer. A lasting lesson may be learned from the fractional quantum Hall effect and Kitaev's models. We witness gauge phenomena emerging as collective effects in systems with just close-proximity links. It's intriguing to think that the gauge symmetries observed in nature could have a similar origin.

CONCLUSION

It is appropriate to consider how the discovery of quantum error correction and fault tolerance may have an impact on basic physics given how much it has changed our understanding of quantum information. In reality, the physics world has been perplexed by a basic problem involving the loss of quantum information for more than 20 years. Our recently gained knowledge of fault-tolerant quantum processing gives us a novel and possibly beneficial approach to thinking about this issue. We could suppose that localized processes that obliterate quantum information are relatively prevalent in Kitaev's spin models. However, if we were to study the development of the system with a coarser resolution, focusing just on the data contained in the charges of far spaced quasiparticles, we would be able to witness unitary evolution with extraordinary accuracy and would not be able to see any sign of the underlying chaos. Likely, Nature has included fault tolerance into her architecture, hiding the quantum noise at the Planck scale from our view. This is an intriguing theory. The finding that quantum systems may be stabilized by appropriate coding techniques leads us to wonder if nature is fault tolerant. If this is the case, quantum mechanics may rule (with good precision) at intermediate length scales but may struggle at both the Planck scale (where "errors" are frequent) and at macroscopic scales (where decoherence is quick).

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