Recent developments in quantum computation with trapped ions, superconducting circuits, and nitrogen-vacancy centers in diamond

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Abstract: Quantum computation is widely regarded as the next generation of computing technology. Owing to quantum entanglement and true parallel computing ability, it promises to exponentially or dramatically exceed classical computers on certain problems, such as factoring and unstructured database searching. Although tremendous progress has been made in the last decade towards realizing a practical quantum computer, quantum error correction and scale-up of quantum systems remain the most challenging tasks. Among all candidates for quantum computing systems, trapped ions, superconducting circuits, and nitrogen-vacancy centers in diamond are the three most attractive and promising approaches. Here, we focus on the recent developments towards quantum error correction, scalable quantum computation, and the demonstration of quantum supremacy in these three systems.

摘要：基于量子力学的量子信息科技作为后摩尔时代的新技术代表着 21 世纪信息科学的发展方向，量子计算机的研究将引起信息科学领域革命性的发展。目前有望实现量子计算的最主要量子系统包括束缚离子、超导电路、金刚石色心等。束缚离子系统具有优异的相干性能，以及由此可以实现超高保真度的量子逻辑门，因而引领着量子计算的物理实现。超导量子电路系统因其基于固态材料，可以利用现存的半导体工艺实现大规模集成化，同时具有优异的相干性能，已经成为量子计算领域最可行的平台之一。超导量子计算需要超低温环境，而基于金刚石色心的量子计算能够在室温下进行，且无需真空环境，因此引起了人们极大的兴趣。由于量子信息的脆弱性，在量子计算中不可避免地会出现错误。为此人们设计了量子纠错码来纠正错误。要实现可容错量子计算，通用逻辑门保真度与单发量子测量保真度均需超过 99%。要真正超过经典计算机的计算能力，展示量子计算的优越性，需要 50 个以上的可控量子比特。针对上面提到的 3 个量子系统，我们分别介绍了实现量子纠错，可扩展量子计算进而展示量子优越性的实验进展。目前，这 3 个系统中的量子逻辑门保真度与单发量子测量保真度均达到表面码量子纠错码的阈值。有望在不久的将来，实现可容错的实用量子计算机。

In a landmark paper published in 1981, Richard Feynman pointed out that quantum computers, once they appear, could be a universal simulator for various physical systems [1]. Compared with a classical computer, a quantum computer should be the perfect simulator for quantum systems, such as strongly correlated many-body systems. The computational complexity for strongly correlated quantum systems increases exponentially as the number of particles increases, which prevents efficient simulation on classical computers.

One of the most famous quantum algorithms is Shor’s algorithm [2]. Shor’s algorithm was invented in 1994, and stimulated a worldwide enthusiasm in quantum computing. Shor’s algorithm solved a difficult problem: given a large integer, find its prime factors. The best known classical algorithm for this problem works in sub-exponential time. Shor’s algorithm, however, runs in polynomial time, which is a substantial improvement.

As is well known, the quantum state is very fragile to noise. The advantage of quantum computation will disappear if we cannot maintain quantum coherence in the quantum computer. During the last two decades, great progress has been made in quantum computation. Fault-tolerant quantum computation theory was established at the end of 1990s [3]. As long as the quantum logic gates and quantum measurement fidelity are sufficiently large, the errors arising from decoherence and controlling infidelity can be corrected. The best-known error correction code is the surface code, whose threshold of gate infidelity is around 1% [4].

Among the candidates for quantum computing, trapped ions, superconducting circuits, and nitrogen-vacancy (NV) centers in diamond are most attractive and promising. In this paper, we focus on the recent developments towards quantum error correction (QEC), scalable quantum computation, and the demonstration of quantum supremacy in these three systems.

Current developments in trapped ion quantum computation

A trapped ion system is one of the leading candidates for quantum computers, quantum simulators, and quantum repeaters [5]. A system with a small number of qubits has fully fulfilled all the basic requirements (DiVincenzo criteria [6]) for the realization of quantum computation and quantum communication. For quantum computation, ion qubits have demonstrated near-ideal initialization and detection, a universal set of quantum operations, and long coherence time [7,8]. For quantum communication, ion qubits have been inter-converted to photons and two different nodes have been connected through the photonic link [9].

In a trapped ion system [7,8] as shown in Fig. 1, the qubit is the two internal levels of an atomic ion, which is stably confined in a 3D harmonic potential. The initialization to one state of the qubit is performed by the standard optical pumping technique, and the discrimination of the qubit state is achieved by a state-dependent fluorescence detection. A single-qubit quantum gate is operated by the application of a resonant microwave or laser beam to the qubit level, and the two-qubit controlled gate is realized through the collective excitation of the motion of ions. The atomic ions, also known as stationary qubits, have well-defined optical transitions that can be inter-converted to photons, also called the traveling qubits [9].

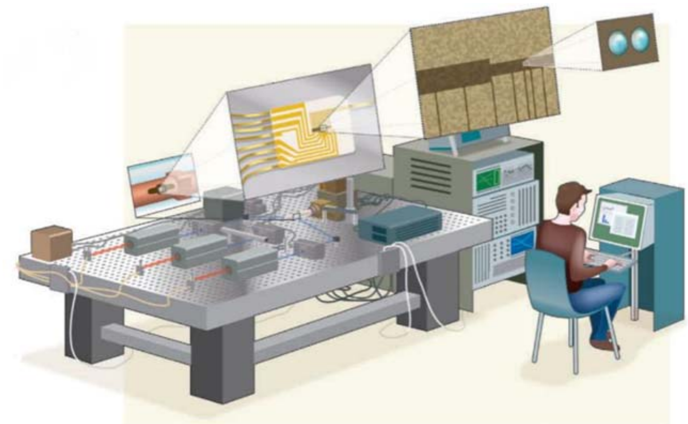

Figure 1 Schematic of an ion trap quantum computer. (Reproduced with permission from Knill E, *Nature* 463, 441 (2010). © 2010 Nature Publishing Group.)

Currently, the trapped ion systems have been developed to the level of showing quantum supremacy, which outperforms classical computations for a certain complex problem, as shown in Fig. 2. A fully controllable quantum system with over 50 qubits is known to be impossible to compute or simulate even with the most powerful classical super-computers available today [10]. Therefore, the realization of such large quantum systems is required for a demonstration of quantum supremacy.

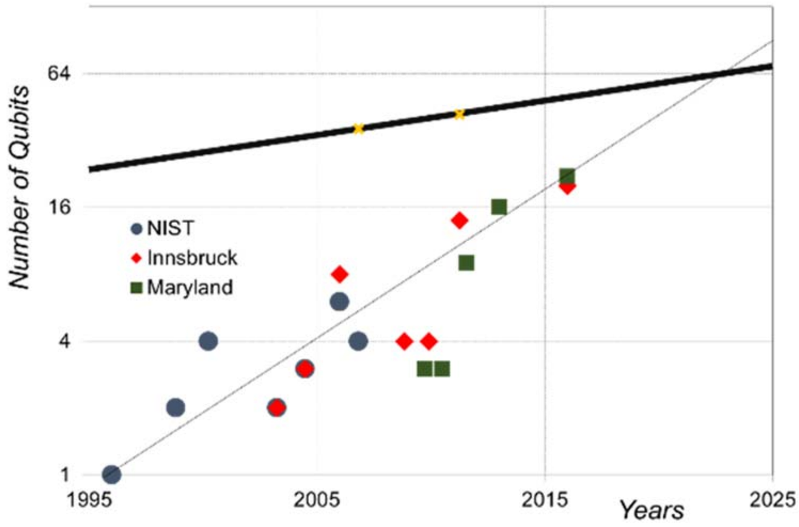

Figure 2 Increase of the number of qubits that are coherently manipulated in the trapped ion system. The thin black line is a guide line to show the increase in the number of ion qubits. The thick black line represents the developments of classical computation, which connects the two yellow points that show the results of classical computation (36 qubits in 2007 shown in Ref.[10], 42 qubits in 2010 shown in Ref.[11](Reproduced with permission from Ref.[10], Copyright © 2006, Elsevier B.V.All rights reserved).

The architectures for scaling up the number of qubits in trapped ion systems can be categorized by the following three main routes: 1) multi-ions in a single trap; 2) multi-zones connected by shuttling ions; 3) multi-traps connected by photons. We describe the three architectures independently, but the relations are rather more complementary than competitive and all of them can be constructively combined for an ultimate quantum computer based on trapped ion technology.

Single-trap architecture

The original proposal of trapped ion quantum computation is based on multiple ions in a linear geometry with individually addressing laser beams in a single trap [12]. The original approach relies on only a single vibrational mode for the entangling operation of more than two qubits, which has growing difficulty in resolving the single mode from the increasing number of collective motional modes as the number of ions increases. Nevertheless, up to 14 qubits, the single-mode scheme works well and has shown quantum entanglement above the classical threshold [13]. The 14-qubit entanglement is realized without control of the individual ions. With the individual addressing of ions, many diverse important quantum protocols have been demonstrated up to seven qubits including digital quantum simulation [14], repetitive QECs [15], color code [16], realization of the factorization algorithm [17], simulation of lattice gauge theory [18], and so on.

The limitation of a single-mode scheme can be overcome by simultaneously using multiple motional modes, which can allow a much greater number of qubits to be coherently operated in a single trap [19], as shown in Fig. 3(a). For the usage of multi-modes, the transverse modes are the appropriate choice because the frequencies of the modes are closely spaced, and the highest frequency is independent of the number of ions [19]. The transverse mode scheme has been demonstrated for the creation of the entanglement [20] and extended for the simulation of a quantum magnet with up to 20–22 qubits [21,22,23,24,25]. The multi-mode scheme has been applied to universal quantum computation with up to five ions [26,27]. Compared with the systems for quantum simulations in Refs.[21,22,23,24,25], which attempt to solve a particular problem, the realized five-qubit device is fully capable of arbitrary quantum operations, which is technologically more advanced.

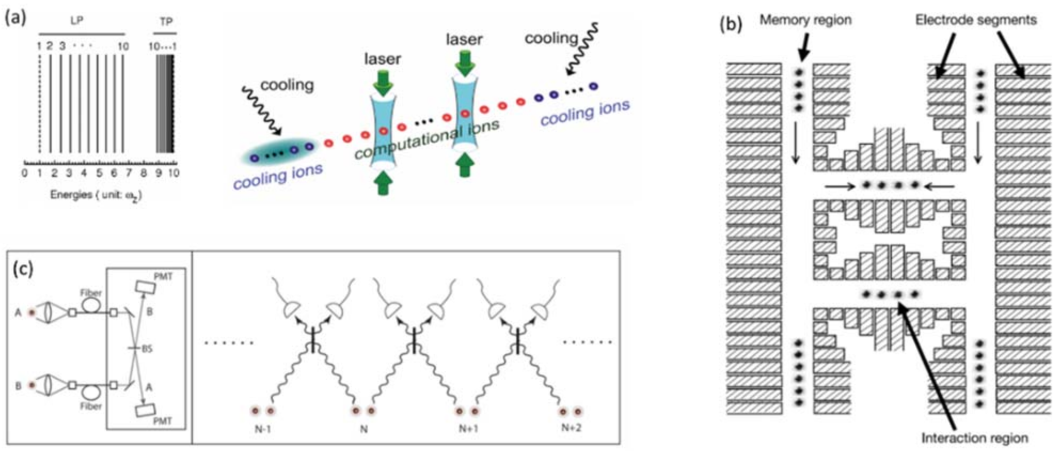

Figure 3 Three architectures of scaling up the trapped ion system: (a) a single-trap architecture (reproduced with permission from Lin G D, et al. *Europhys. Lett.*, 86, 60004 (2009)); (b) multi-zone architecture (reproduced with permission from Kielpinski D, et al. *Nature* 417, 709 (2002); © 2002 Nature Publishing Group); (c) photon connection architecture (reproduced with permission from Luo L, et al. *Fortschr. Phys.*, 57, 1133 (2009); © 2009 John Wiley and Sons).

The multi-mode scheme would not have any fundamental limitation in increasing the number of qubits to several hundred [18]. The main limitation of the scheme could come from the lifespan of the ion crystal, which is reduced by collisions with the background gas in the vacuum system. One potential solution to enhance the lifetime is to put the whole ion-trap system in a cryostat environment at around 4 K, where the energy of the background gas and the vacuum level can be significantly reduced by several orders of magnitude.

An alternative method of holding multiple ions in a single trap is to use a Penning trap that confines ions with a strong magnetic field instead of a rotating electric field. In the Penning trap, hundreds of ions can form a 2D hexagon lattice rotating with the cyclotron frequency. It is extremely difficult to implement individual control of ions in the Penning trap and to fully resolve a motional mode. Nonetheless, the global application of Ising-spin interaction on the ion lattice [28,29] and the spin-squeezing effect have been observed. Recently, schemes combining the advantages of the Paul trap and the Penning trap, i.e., the 2D ion trap without rotation, have been proposed [30], but no experimental demonstration has been reported so far.

As we approach the time of surpassing the limitations of classical computation with quantum computation, the question of what problem can clearly show quantum supremacy is being discussed seriously. It is well known that it is impossible to classically compute and simulate a fully controllable quantum system with over 50 qubits. However, this does not mean that any demonstration in the system is outperforming classical computations. The simulation of frustrated quantum magnets, time evolution of quenched Hamiltonians, computation of a molecular structure, quantum field theory, and so on have been investigated as representative problems for quantum supremacy. Among such classically intractable problems, the boson sampling problem is the most well-defined problem to demonstrate quantum supremacy, which is classically intractable, even approximately, unless the established hierarchy of computational complexity collapses [31]. The trapped ion system can perform the boson sampling of phonons with the advantage of deterministic preparation and detection of individual quanta over the photonic system [32,33]. The experimental realizations of basic protocols including phonon number resolving detection [34], deterministic addition and subtraction of single quanta of phonons [35] have been reported and extended to create a highly entangled NOON state with nine particles [36].

Multi-zone architecture with ion-shuttling

The difficulty of operating many ions with a single motional mode in a single trap can be resolved by separating the operation zone and the memory or storage zone, which are connected by moving ions from one zone to the other [37], as shown in Fig. 3(b). The multi-zone approach can be modularized, which allows extensive expansion of the number of qubits. For the realization of the multi-zone architecture, reliable ion-shuttling trap technology must be developed that avoids serious heating of the motion and includes different species of atomic ions for cooling ions after the shuttling. The basic building blocks for the operation zone of the trapped ion system involving ion-shuttling with cooling ions have been demonstrated [38]. Recently, an approach using cooling ions as a quantum resource has also been demonstrated [39,40].

The gate fidelities in the operation zone have been seriously pushed to reach a fault-tolerant level. Recently a single-qubit gate with 99.9999% fidelity has been achieved [41]. For the two-qubit gate, a few groups have demonstrated a fidelity of 99.9% [42,43], where the main limitation comes from the spontaneous emission of the laser beams of the operation. The coherence time of a single qubit in memory zone has also been extended from a few tens of seconds to over ten minutes.

Since the multi-zone approach demands many lasers and one major source of infidelity is the laser beams, two-qubit gate operations without laser beams have been investigated. The laser beam can be replaced by a microwave with a large gradient in strength or in an external magnetic field. High fidelity has been demonstrated in the laser-less gates [44,45].

Meanwhile, the surface ion trap technologies have also been seriously investigated for the realization of a multi-zone architecture in Sandia National Lab and Georgia Tech Research Institute. Several efforts integrating optics in the surface trap have been realized even in the cryostat environment [46].

Photonic connection

The photonic connection provides a network of qubits at any distance and the photonic link can cooperate with either single-trap or multi-zone architecture [9], as shown in Fig. 3(c). The basic protocol of inter-conversion between ion qubit and photon, and the connection between separated ion qubits through a photonic link have been demonstrated. The local motional gate and the photon gate are also experimentally implemented in one system [47]. Although the protocol of photonic connection is probabilistic, it has been theoretically shown that the entire process can be fault-tolerant [48]. Moreover, the photonic link can couple different physical platforms including quantum dots [49], NV centers in diamond, and ensembles of atoms.

One disadvantage of the photonic connection is that the success of the photonic link occurs at a very slow rate. The rate can be increased by the efficient collection of photons, which can be achieved by using a high-numerical-aperture (NA) lens [50] or putting ions inside a cavity [51,52,53]. An enhancement in collection of around a factor of 20 by the high-NA lens has been reported and various cavity systems have been realized.

Currently among these three approaches, it seems that the single-trap architecture is closest to showing quantum supremacy. It is not easy to imagine what kind of consequence we would observe after the first demonstration of a quantum computer that outperforms a classical computation even for a single problem. After demonstrating the typical quantum supremacy, the ion trap quantum computer can be further improved to scale up to the next level by accommodating the technology of ion-shuttling or photonic connection.

Quantum error correction with superconducting circuits

Quantum information processing (QIP) promises to exponentially or dramatically exceed classical computers on certain problems (factoring and unstructured database searching) because of quantum entanglement and true parallel computation. According to Devoret and Schoelkopf [54], seven steps are required to build a fault-tolerant quantum computer, as shown in Fig. 4. In the last decade, tremendous progress has been made towards realizing such a practical quantum computer. The first three steps have been demonstrated: operations on single physical qubits, algorithms on multiple physical qubits, and quantum non-demolition (QND) measurements for error correction and control. However, a practical quantum computer is required to operate on the so-called logical qubits with hopefully infinitely long lifetime. Therefore, the next step is to use QEC to overcome the fragile nature of quantum information on physical qubits, and through QEC to achieve a logical memory or logical qubit with longer lifetime than its individual physical qubit components. Once a QEC-protected logical memory is realized, to achieve the ultimate fault-tolerant quantum computation, the final two steps are to repeat operations and algorithms at the logical qubit level.

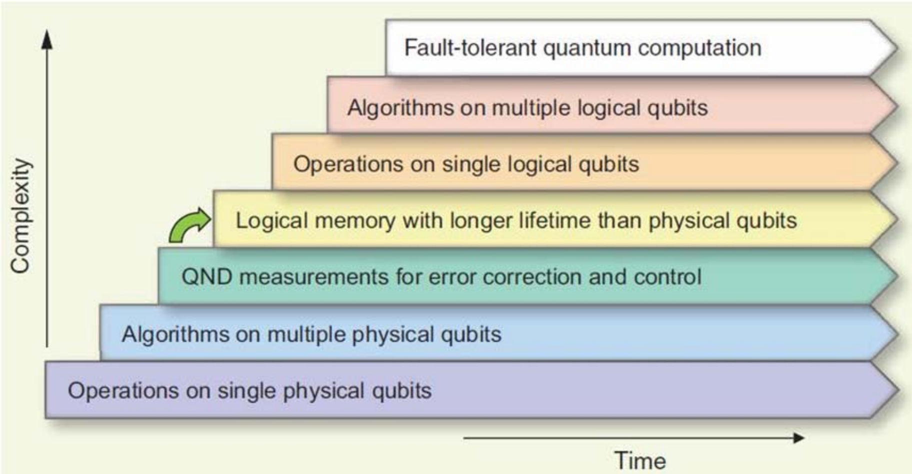

Figure 4 Seven stages to realize fault-tolerant quantum computation. So far, no quantum memory or logic qubit protected by QEC has ever been demonstrated. The realization of such a quantum memory or logic qubit is considered to be one of the most urgent goals for the field of quantum computation. (Reproduced with permission from Ref. [54], © 2013 The American Association for the Advancement of Science.)

So far, the fourth stage has not yet been fully demonstrated in any quantum system. A proof-of-concept experiment of QEC based on three qubits has been demonstrated in various physical systems including trapped ions [15] and superconducting qubits [55]. However, neither experiment has shown that the performed QEC can actually outperform the natural decoherence of the encoded quantum information. Therefore, the realization of QEC is one of the most urgent and challenging goals in QIP. Here, we focus on the recent experimental efforts towards this goal with superconducting circuits.

Superconducting circuits utilize two robust physical phenomena, superconductivity and the Josephson effect, to realize the key ingredients: superconducting qubits and resonators both with great quantum properties (Fig. 5). Superconducting circuits have the following advantages. First, superconducting qubits are macroscopic "artificial atoms" whose parameters can be flexibly designed; therefore, it is easy to achieve a strong coupling between qubits and resonators. Second, superconducting circuits are based on solid-state devices and are ready to scale up with current integrated circuit technology. Third, superconducting qubits have large coherent time to gate operation time ratios, allowing for a large number of operations before losing coherence. Finally and most importantly, there is no known physical law to prevent further improvement of the quantum property of both superconducting qubits and resonators. As a figure of merit, qubit coherence has been increased by more than five orders of magnitude in less than two decades. Owing to the above advantages, superconducting circuits, in particular, circuit quantum electrodynamics (cQED) architectures have become the leading and most promising platform for QIP. Large information companies, such as Google, IBM, and Intel, have invested greatly in superconducting quantum computation. Very recently, Google demonstrated the power of quantum annealing based on D-wave's 2X quantum processor with more than 1,000 superconducting qubits [56]; IBM launched a free quantum computing cloud service based on a processor with five superconducting qubits [57].

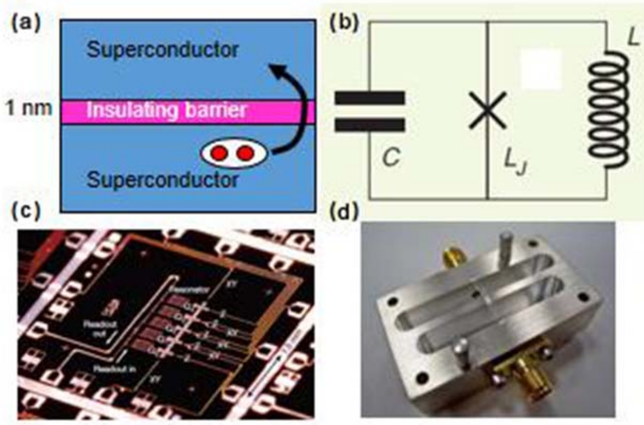

Figure 5 (a) Schematic of a Josephson junction, the most critical ingredient of a superconducting qubit: two superconductors are separated by a thin insulating barrier with Cooper pairs that can tunnel across. (b) Superconducting qubits can be described as a parallel combination of an inductor L, a capacitor C, and a Josephson junction L_J. (c) Optical image of an integrated Josephson quantum processor with five Xmon qubits (reproduced with permission from Ref. [60], © 2015 Nature Publishing Group). (d) Optical image of a transmon qubit in a waveguide trench coupled to two 3D cavities (reproduced with permission from Ref. [63], © 2014 Nature Publishing Group).

The basic scheme of QEC is to redundantly encode quantum information in a subspace of a large Hilbert space, which is called the code space. Errors will change the code space into error spaces. One requirement is that those error spaces be orthogonal to each other and also to the code space, so they can be distinguished by error syndrome measurements. The error syndrome measurement, however, should not gain any knowledge of the encoded information; otherwise, the measurement back action will cause quantum information leakage. A measurement-based QEC requires the measurement of error syndromes in a QND way and at a rate that is faster than the rate at which errors occur.

The traditional QEC approach using multiple physical qubits to encode one logical qubit remains very challenging because of the extremely low gate error threshold, typically below 10^{-4}, and the huge resources required for concatenate encoding. In superconducting quantum computation, there are two other main approaches towards QEC. The first is called the surface code [58], which only requests nearest-neighbor coupling and is a mainstream approach. This approach needs relatively high error rate, as high as 1%, but it also requires large resource overhead, usually thousands of physical qubits per logical qubit. The theoretical part has been well understood and what remains are mainly engineering and technical issues. In 2014, the Martinis group (now at Google) used a five-qubit processor demonstrating that both single-qubit and two-qubit gate fidelities are as high as 99.92% and 99.4%, respectively, larger than the surface code threshold [59]. As a further demonstration, they also constructed a five-qubit Greenberger–Horne–Zeilinger (GHZ) state with a fidelity of 81.7%. However, in this work, the five qubits are arranged in a linear array instead of the required chequerboard pattern. In a subsequent study [60], with a nine-qubit version also in a linear array, the same group demonstrated the protection of the GHZ state from environment-induced bit-flip error using a repetitive code, which is a one-dimensional variant of the surface code. At about the same time, DiCarlo's group at Delft University of Technology also demonstrated the detection of bit-flip errors in a logical qubit using stabilizer measurements [61].

The other approach initiated by the Yale group [62] is based on encoding into photonic states in a microwave cavity instead of superconducting qubits. The main advantage is the hardware efficiency: each module contains only one microwave cavity, one ancillary superconducting qubit, and one readout channel. Microwave cavities are attractive resources for QIP for the following reasons. First, as a harmonic oscillator, a microwave cavity has infinite-dimensional Hilbert space, large enough for the redundancy of information encoding. Second, a microwave cavity has superior coherence properties, i.e., the coherence time can be of the order of 10 ms or $Q > 10^8$, which is good for quantum memory in the first place. Third and most importantly, in the large Hilbert space, there is still only one main type of error: photon loss. This is different from the traditional QEC code in which more error channels are introduced when more physical qubits are involved. Therefore, there is only one error syndrome: the photon number parity needs to be monitored for this approach. If the errors in real time can be tracked, one can track the encoded information and correct it at the end of tracking. This is a unique and exciting direction towards a module-based QEC scheme. Once a QEC-protected quantum memory is realized, the ancillary qubit can be used for distributing entanglement and operations between different modules.

One particular encoding scheme is to use the Schrödinger cat state, superposition of coherent states with opposite phases, in a microwave cavity to encode quantum information. The key idea of this approach is to track the error syndrome, photon parity, continuously and in a non-demolition way in real time. This essential part was demonstrated in 2014 [63]. In a subsequent study [64], with the help of field programmable gate arrays (FPGAs) for feedback control, the break-even point is finally reached. The lifetime of the stored information on cat states after correction is 10% longer than the best physical qubit of the system, which is |0> and |1> Fock state of the resonator. This is the first realization of a quantum memory of an unknown bit of quantum information actually protected with an extended lifetime by active means, demonstrating the promise of cat states as the basis for QEC. After realizing such a quantum memory with a “memory” qubit (the cat states) and a “communication” qubit (the superconducting qubit), the natural next step is to achieve an entanglement between different “memory” qubits by an interaction and appropriate measurements of the two “communication” qubits. The following step is then to demonstrate how to turn such quantum memories into logic qubits and how to perform universal quantum gates on them [65]. The realizations of a quantum memory and eventually a logic qubit represent significant progress towards a practical quantum computer.

Regarding entanglement distribution, a robust concurrent remote entanglement between two superconducting qubits has also been demonstrated recently [66]. In this work, a novel microwave photon detector was implemented in the superconducting cQED architecture. Although the generation for the remote entanglement pairs has a low fidelity of 0.57 at a low rate of 200 Hz, this work sheds light on the implementation of a modular architecture of QIP with superconducting qubits.

Along the same path, another theoretical proposal based on photonic state has attracted a great deal of attention [67], in which the encoding bases are superpositions of Fock states with binomial coefficients instead of cat states. The resulting advantages include a smaller mean photon number, exact rather than approximate orthonormality of the code words, and an explicit unitary operation for repumping energy into the photon mode. This binomial code can exactly correct errors that are polynomial up to a specific degree in photon creation and annihilation operators, including amplitude damping and displacement noise. As opposed to the cat codes, where corrections can be performed at the end of error-syndrome tracking, the errors need to be corrected immediately.

In summary, QIP is beginning one of its most exciting phases of development. QEC, the holy grail of quantum computation, is within reach of the current techniques. While superconducting quantum computing keeps making steady progress, QEC becomes more than a theoretical discipline to retain the coherence in complex quantum systems. Combined with the continual development of both scientific understanding and engineering techniques, it is optimistic to anticipate a fully QEC-protected logic qubit to be realized in the near future.

Fault-tolerant scalable quantum computing using NV centers

Among all the candidates, only NV centers could operate at room temperature, which makes them very attractive. An NV center is a point defect in diamond. As shown in Fig. 6, it consists of a substitutional nitrogen and lattice vacancy pair. The NV center could be negatively charged or neutral. Both negative and neutral NV centers have sharp zero-phonon lines. For negative NV centers, there are three electron spin states m_s=0, ± 1, whose zero magnetic field level splitting is 2.87 GHz. The coherence time for these states is of the order of milliseconds at room temperature. The NV centers electrons spins could be polarized by a 532 nm laser at room temperature. The zero-phonon line fluorescence is around 637 nm. The fluorescence strength, which is related to the NV center electron spin states, could be used for reading out the NV center states. Furthermore, the NV center spin state manipulation can be achieved by resonant microwave radiation. There are many nuclear spins near NV centers electrons spins, such as ^{13}C. The coherence time of the nuclear spins is of the order of seconds at room temperature. In NV centers, nuclear spins and electron spins couple with each other. The universal quantum logic gates could be realized in NV centers even at room temperature.

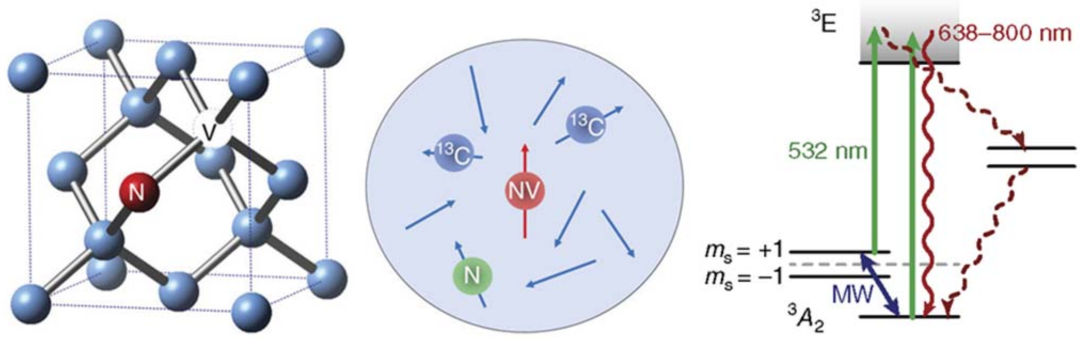

Figure 6 Left: lattice structure of diamond with a nitrogen vacancy center. Middle: spins near the NV center, ^{13}C nuclear spins and N electron spins. Right: negatively charged NV center electron energy levels. Electron spin polarization and readout can be performed by a 532 nm laser, and the fluorescence detection is around 637 nm. The ground state triplet has a zero magnetic field splitting of 2.87 GHz. (Reproduced with permission from *Nature Communications*, 3, 858 (2012), © 2012 Nature Publishing Group.)

To realize fault-tolerant quantum computing in NV centers, we should design quantum logic gates which are robust to the errors. It is found that all geometric-based quantum computation has built-in noise-resilience features. The geometric quantum gates are robust to fluctuations in the controlling field. In 2014, universal quantum logic gates based on geometric phases were reported in NV centers systems [68]. The intrinsic error per gate is less than 1% in the experiment, which clearly shows the noise-resilience features of the geometric quantum gates. The gates fidelity can be further improved by optimizing the controlling pulses shapes. In 2015, a universal set of high-fidelity quantum logic gates was realized in NV centers [69]. A composite pulse technique was developed for suppressing noise in single-qubit gates in NV centers. It was found that the fidelity of a single gate could be larger than 0.9999. For two-qubit gates, a quantum optimal control method was adopted, and controlled-NOT (CNOT) gate fidelity reached 0.9992. As fault-tolerant quantum computation only requires quantum logic gates larger than 0.99, the NV-center-based quantum gates are already at the threshold of fault-tolerant quantum computing.

The next step for reliable quantum computing is error correction. The error correction for all kinds of errors has not been experimentally realized in NV centers. In the last 2 years, several experiments have shown that special types of errors could be detected and corrected in NV centers [70,71]. To detect the errors, the single shot measurement of NV centers should be realized in experiments at low temperature around 10 K. These experiments shown that the phase-flip errors could be corrected in NV centers systems. To correct phase-flip errors, at least three physical qubits are needed. Therefore, in experiments, in addition to NV centers, the nearby nuclear spins are also used. If we want to correct both phase-flip and bit-flip errors, at least five qubits are needed. Therefore, we need to couple at least four nuclear spins to the same NV centers. This is experimentally challenging, but in principle it is possible.

The practical quantum computation requires not only reliable, but also large-scale qubits. However, as natural NV centers are located randomly in diamond, which is the hardest material, coupling two NV centers in a controllable way is very challenging. How to scale the NV center qubits is one of the most difficult problems for building a practical quantum computer with NV centers.

To directly couple two NV centers, we must inject NV centers in diamond with uniform distance. The distance between the nearest NV centers should be of the order of 10 nm. However, when NV centers increase in a single diamond chip, the noise strength increases much faster. To maintain the quantum gates fidelity within the fault-tolerant threshold, the number of NV centers in a single chip should be strictly limited. If we can link NV centers between distant diamonds, they can form a quantum network. Scalable quantum computing is possible.

In 2014, unconditional quantum teleportation between distant NV centers, which were located in two diamonds at a distance of 3 m, was reported in experiments [73]. One year later, the same group generated entanglement between two NV centers at a distance of 1.3 km [74]. They performed a loophole-free Bell inequality test using the two entangled NV centers. These experiments indicated that generating a large-scale quantum network among NV centers using a post selection method is possible in principle. However, the photon emission efficiency of the zero-phonon line of the NV center is around 1%, which greatly limits the efficiency of the post selection method. To enhance the zero-phonon line and the photon collection efficiency, NV centers are coupled with the nearby cavities. By carefully tuning the cavity mode frequency and the decay rate, it is found that the zero-phonon line emission efficiency could be increased to be larger than 50% [75]. In the experiment, the cavity optical quality approaches 10,000, with the NV center electron spin coherence time exceeding 200 μs, which is almost unaffected by the cavity. In this way, the efficiency of the post selection method has been greatly enhanced.

To realize fault-tolerant and scalable quantum computation in NV centers, all these experimental techniques should be combined into a single experiment. As shown in Fig. 7, the distributed quantum computer could be formed by many small quantum processors, which contain at least five physical qubits [72]. A high-fidelity universal set of quantum gates among NV centers should be achieved in each register. Using the post selection method, distant NV centers could be projected into entangled states, and finally form a large quantum network in polynomial time. Near the NV centers, photonic-crystal-based cavities are used to enhance the zero-phonon line and the photon collection efficiency approaches unity. Therefore, the success possibility of post selection could be greatly enhanced. In this way, the reliable and scalable quantum computer could be made by NV centers in future.

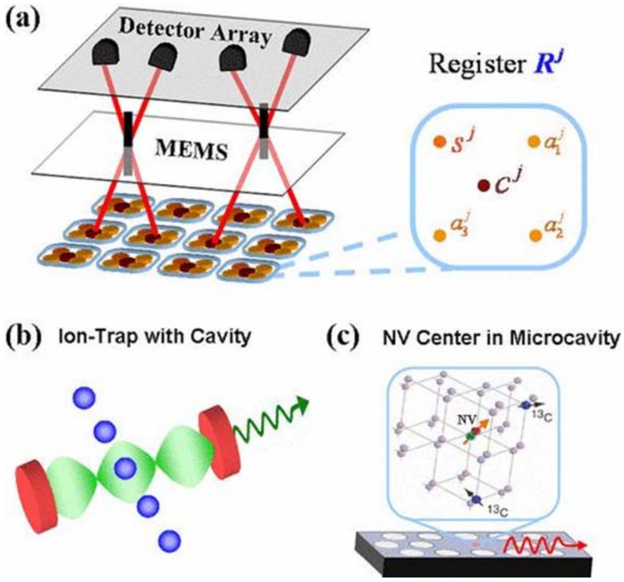

Figure 7 Distributed quantum computer based on many small registers. Each register has at least five qubits. Local operation on the qubits should have very high fidelity to fulfil the fault-tolerance requirements. Entanglement between distant registers could be realized using a post selection method. (Reproduced with permission from Ref. [72]. © 2007 American Physical Society.)

Closing remarks

The ion trap system has been one of the leading systems for the realization of a quantum computer and it has been clearly demonstrated that there would be no fundamental limitations to building it. In the near future, ion trap quantum computers are expected to be able to perform classically intractable operations with a few dozens of qubits, using the single-trap approach. The largest challenge in the single-trap approach with dozens of qubits would be the lifetime of the ion crystal limited by the background gas collision. This limitation can be resolved by placing the ion trap system in a low-temperature environment around 4 K. For the universal quantum computer with thousands of logical qubits, a long-term development and investments involving ion-shuttling or photonic connections would be required. If a scalable unit of a logical qubit accommodating existing high-fidelity gates is developed, the realization of universal quantum computation can be accelerated.

The superconducting circuit system has become one of the most promising platforms towards to a practical quantum computer, as evidenced by the huge investment from the large commercial companies. The main challenge for quantum computing based on superconducting circuits is to integrate more qubits with high-precision quantum manipulations while maintaining their coherence properties. Along this direction, the surface code approach is making steady progress and hopefully can scale up the system enough to realize QEC. This certainly requires careful microwave engineering and sophisticated nanofabrication techniques. For the other approach using photonic states to encode quantum information, the strategy is different: to perform error correction on single logical qubits first and then to scale up the quantum system robustly. Tremendous progress has also been made in this direction; however, there may be other remaining associated errors to be understood better in the future.

The challenge for quantum computation based on NV centers is the scalability. We should design and realize the high-fidelity and efficient quantum interface between the NV centers spins and the flying (photonic) qubits. In this way, a large-scale quantum network may be achieved in NV centers, and the scalable quantum computation can be realized in this platform. More efficient QEC codes based on NV center spins qubits are also needed. With the development of high-quality quantum gates, quantum interface fidelity, and efficient QEC codes, we hope that, in the next few years, fault-tolerant quantum computation based on NV centers could be realized in experiments.

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