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PHYSICS

A new epoch of quantum manipulation

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ABSTRACT

The behavior of individual microscopic particles, such as an atom (or a photon), predicted using quantum mechanics, is dramatically different from the behavior of classical particles, such as a planet, determined using classical mechanics. How can the counter-intuitive behavior of the microscopic particle be verified and manipulated experimentally? David Wineland and Serge Haroche, who were awarded the Nobel Prize in physics in 2012, developed a set of methods to isolate the ions and photons from their environment to create a genuine quantum system. Furthermore, they also developed methods to measure and manipulate these quantum systems, which open a path not only to explore the fundamental principles of quantum mechanics, but also to develop a much faster computer: a quantum computer.

Keywords: quantum manipulation, quantum computation, optical clock, ion trap, cavity QED

INTRODUCTION

Serge Haroche and David Wineland were the 2012 Nobel Laureates in Physics. They were jointly awarded the prize 'for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems' [1]. Their achievements involve individual (or a few) atoms and photons, which are the fundamental particles in quantum physics. Wineland worked on the ion trap system that traps the ions in an electromagnetic potential. He and his group developed methods (in particular, the sideband cooling method) to cool the ions to their ground state without phonons, by interacting with laser fields. Using these technologies, the ion trap is an ideal system to test the fundamental principles of quantum mechanics, to demonstrate the feasibility of the quantum computation and to improve the accuracy of the clock standard. Haroche focused on developing a cavity with extremely high Q ($\sim 10^{10}$) to confine one (or several) photons. A Rydberg atom is used to interact with the field in the cavity. The interaction should be significantly strong because of the high Q, making it a good detector for monitoring the field. With the aid of a quantum non-demolition measurement, this system could be a very good platform to test quantum information theory and fundamental problems in quantum mechanics, especially the decoherence processes. Their achievements are not only very important for fundamental quantum mechanics, but they also paved the way for quantum technologies, such as quantum computation. In the following, we introduce their experimental methods and their applications.

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QUANTUM MECHANICS AND QUANTUM COMPUTATION

Quantum mechanics and general relativity are the two pillars of modern physics. Quantum mechanics provide the basic principles for the microscopic world, and general relativity describes the large-scale universe. Quantum mechanics has been successfully used to understand experiments at the atomic scale. However, its foundation remains not well understood after $\sim$100 years of effort. Unlike general relativity, which is based on very simple assumptions, quantum mechanics is based on more complex explanations. According to the Copenhagen interpretation, quantum theory includes three basic parts: representation, evolution and measurement.

The state of a quantum system is represented by a vector: vectors with the same direction and different lengths correspond to the same quantum state, and all the states form a Hilbert space. Based on the structure of the Hilbert space, the quantum state could be a linear superposed state on various bases, which is known as the superposition principle of quantum states:

$$|\Psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle\,, \tag{1}$$

for a two-level system. Here, $|0\rangle$ and $|1\rangle$ are the eigenstates of the two-level quantum system (such as, the spin-1/2 system). For the n-body situation, the superposition leads to the well-known Schrödinger cat state named after the thought experiment proposed by Schrödinger in 1935 (also named a Greenberger–Horne–Zeilinger state) [2]:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle_1 \cdots |0\rangle_n + |1\rangle_1 \cdots |1\rangle_n\,, \tag{2}$$

where the states $|0\rangle_1 \cdots |0\rangle_n$ and $|1\rangle_1 \cdots |1\rangle_n$ have a macroscopic character with a very large n. It implied that the macroscopic system can be in two different macroscopic states simultaneously, such as 'live' and 'dead' for the cat, which is dramatically different from our classical intuition.

The evolution of a quantum system is described by the famous Schrödinger equation:

$$\mathrm{i}\hbar\frac{\partial\,|\Psi(t)\rangle}{\partial t} = H(t)\,|\Psi(t)\rangle, \tag{3.1}$$

or by some time-ordered unitary transformations form such as

$$|\Psi(t)\rangle = \prod_i \mathrm{e}^{-\mathrm{i}\int_{T_i}^{T_i+1} H(t)\mathrm{d}t/\hbar}\,|\Psi(0)\rangle, \tag{3.2}$$

where $|\Psi(t)\rangle$ is the quantum state of the system at time t and $|\Psi(0)\rangle$ is the initial state where $t = 0$. $H(t)$ is a time-dependent Hamiltonian of the system controlling the evolution. For each $H(t)$, we can divide the time t into several segments, in each segment (T_i, T_{i+1}), the Hamiltonian $H(t)$ is almost independent of the time t and the evolution during this segment can be described by the unitary operator $U_i = \mathrm{e}^{-\mathrm{i}\int_{T_i}^{T_i+1} H(t)\mathrm{d}t/\hbar}$. Therefore, the manipulation of a quantum system can be described by some ordered unitary operators and is exactly determined by the Hamiltonian $H(t)$.

The evolution of a quantum state is well defined; however, the results of the measurements are random. A measurement is a subtle process in quantum mechanics and fills the gap between the quantum world and our classical world. A measurement plays a central role in the fundamentals of quantum mechanics. A general measurement must have the following characteristics according to the Copenhagen interpretation (as described in [3]):

- When immediately repeating the same measurement on a quantum system, the same outcome should result.
- Each outcome of a measurement should be one of the eigenvalues of the measured variable, and the final state of the measured system should be one of the eigenstates. This process is called collapse processing.
- The probability of obtaining a special outcome i is determined by $|\alpha_i|^2$, where α_i is the coefficient of the eigenstate i in the state of the measured system.

For the former two-level superposition state (2), the measurement on the basis of the eigenstate will obtain the state $|0\rangle$ or $|1\rangle$ with the probability $|\alpha|^2$ or $|\beta|^2$, respectively. For the n-body cat state (2), we have the same probability of obtaining $|0\rangle_1 \cdots |0\rangle_n$ and $|1\rangle_1 \cdots |1\rangle_n$. Furthermore, if we only measured one of the particles, the entire n-body system also collapses to $|0\rangle_1 \cdots |0\rangle_n$ or $|1\rangle_1 \cdots |1\rangle_n$, and the state is determined by the result of the single-particle outcome. This result means that all of the particles are strongly correlated. This type of correlation (between different particles) extends beyond classical correlation and is called quantum correlation. One of the most important quantum correlations is described by quantum entanglement. Quantum entanglement plays a critical role in quantum information and quantum computation. The power of quantum technologies originates mainly from the entanglement of the quantum system.

The Copenhagen interpretation of the measurement process is partly phenomenological, and the collapse interpretation is not well satisfied. With the simple philosophy that the measurement process is not particularly special and should be described by the interaction between the measurement instrument and the observed system, the entire system (including the measurement instrument and the observed system) can also be described using the Schrödinger equation. A more elegant interpretation of the measurement should unify the measurement process and the evolution. Much research has been devoted to this problem [3]. Introducing decoherence into the measurement process is a promising approach to filling the gap between the classical and quantum world. Generally, a quantum system is not isolated and interacts with its environment. When considering the measurement process, its environment must be included. Thus, the entire system (including the measurement instrument, the observed system, and their environment) can also be described using the Schrödinger equation, and the system components will evolve into an entangled state. Because the environment has a large number of degrees of freedom, it should be Markovian, and the coherent information between the observed system and measurement instrument is completely lost (for the non-Markovian environment [4] the coherence will revive after some time) when we trace out the environment. Finally, the observed system will collapse to a classical ensemble system. Therefore, the decoherence process is one of the fundamental problems in quantum mechanics. Haroche *et al.* developed the cavity technology and Rydberg atom detecting method to extensively investigate the decoherence processes. Therefore, to maintain the coherence (superposition character) of the quantum system, the system must be isolated enough to avoid interaction with the environment, according to decoherence theory. The isolation makes the quantum system able to be precisely manipulated locally using the Schrödinger equation.

One of the remarkable applications of the superposition of the quantum state is that it can be used to design certain quantum algorithms with parallelism and can significantly speed up the computation. The best known quantum algorithm was discovered by Peter Shor in 1994 [5] and later named Shor's algorithm. This algorithm is used to factorize a large number into two prime numbers. Before this algorithm, the most efficient classical algorithm for this problem grew exponentially with the length of the number. Shor's algorithm can solve this problem in polynomial-scaled time, which is extremely efficient. The efficiency of the new algorithm will destroy the security of the widely used Rivest, Shamir and Adleman algorithm.

However, it is not easy to build a system to realize the powerful quantum algorithm in a physical system. The quantum system must satisfy special conditions, which are called the DiVincenzo criteria [6]:

- There are well-defined local qubits, which are isolated two-level systems.
- The entire system can be initialized to some given state, such as $|+\rangle_1 \cdots |+\rangle_n$, where $|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$.
- The entire system has a long coherence time, t_{coh}, which is much longer than the operation time, t_{ope}. The typical requirement is $t_{\mathrm{coh}}/t_{\mathrm{ope}} > 10^4$.
- The entire system can implement a few local quantum gates forming a universal set, generally including single-qubit unitary operations and a two-qubit controlled-NOT (CNOT) gate (or a controlled phase gate). A universal quantum computer can be realized using these gates.
- There is an efficient qubit measurement method to read out the results.
- The system is a scalable system that allows us to coherently manipulate many qubits.

Wineland and his co-workers performed many experiments to demonstrate that the ion trap is an ideal system to realize quantum computation.

In addition, if we are more ambitious in building a quantum network, then the system has additional requirements to connect the quantum computers located at different nodes. Generally, the information transmits between different nodes using flying qubits (photons). Therefore, the state of a stationary qubit (computation qubit) needs to be efficiently converted into a flying qubit.

MANIPULATION OF A SINGLE ION

To obtain a 'pure' quantum system, we need a quantum system that we can isolate from its environment. The most popular individual quantum system is an atom or a photon. Generally, an atom or a photon moves in a vacuum and is difficult to manipulate and measure. Therefore, it is important to be able to confine it. The ion, which is a charged atom, can be trapped in a specific electromagnetic potential using the technique developed by Paul and Dehmelt [7,8], who were awarded the 1989 Nobel Prize in Physics. In general, it is impossible to trap a charged atom in a stationary electromagnetic field because of the analytic character of the field. However, the situation changes when a time-dependent field, varying sinusoidally as $\cos(\omega_{\mathrm{rf}} t)$, where ω_{rf} is the radio frequency (RF), is introduced. The entire instant electromagnetic potential is a trap potential with a saddle point [7,8]. The time-dependent field will make the potential rotation and trap the ion at the saddle point (see Fig. 1). One simple experimental setup is presented in Fig. 2.

Generally, the depth of the trap potential is of several volts, and the kinetic energy of the ions is approximately of the same magnitude. To reach the quantum region (quantized oscillation), the ion should be cooled down after the trapping. The Doppler cooling of the ions is the first important step to trap the ions, which Wineland and Dehmelt proposed in 1975 [9]. (Doppler cooling for neutral atoms, which plays an important role in the realization of Bose–Einstein condensation, was proposed by Hänsch and Schawlow [10].) The laser frequency in the Doppler cooling processes should be tuned to a slightly lower frequency than the transition frequency of the atoms (charged or neutral). Because of the Doppler effect, an atom moving toward the laser with a certain velocity will absorb a photon and will lose momentum $\hbar p$ in the direction of movement. After some time, the photon will then be emitted spontaneously. The spontaneous emission is random in all directions, and the average momentum for different atoms (or the average over a long time for a single atom) will be zero. Generally, the velocity of the atom will be reduced. If we set up two

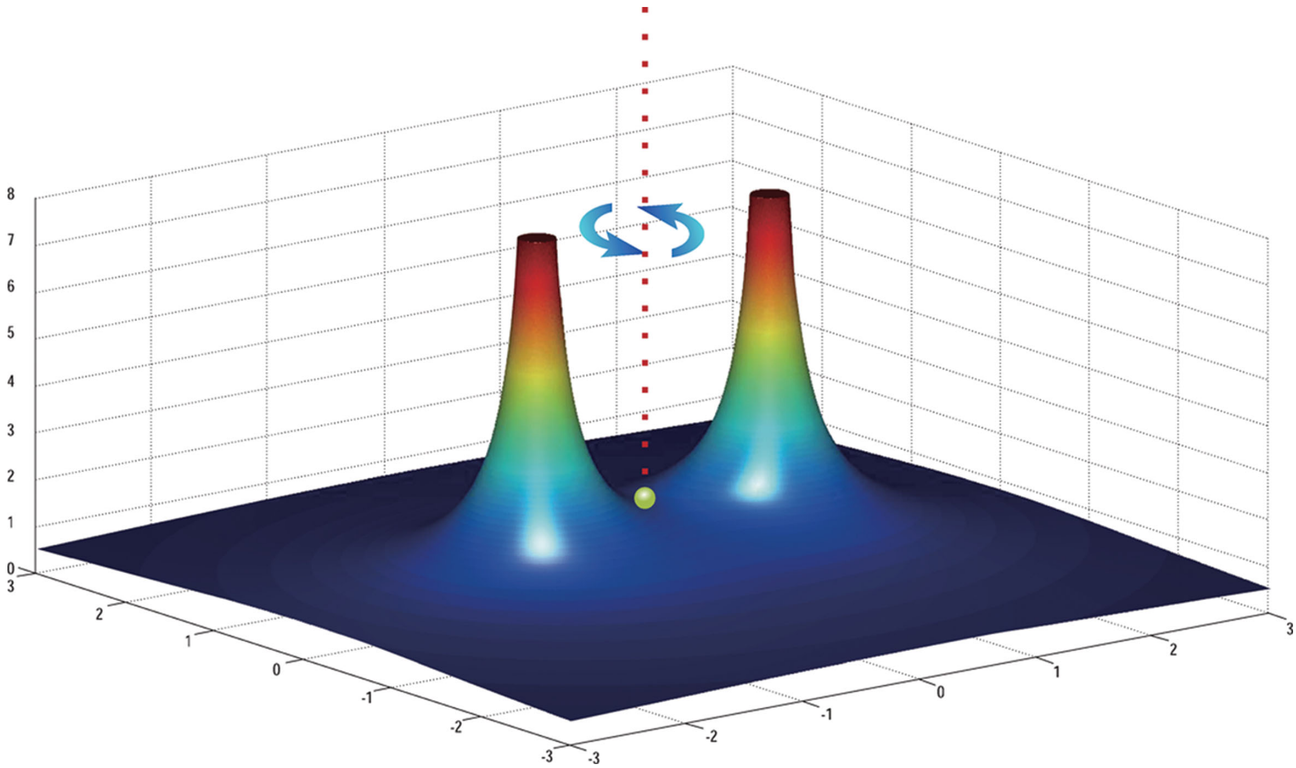

Figure 1. The potential of the ion trap, which is set up as in Fig. 2. A saddle point exists in the instantaneous potential where the ion is not stable. However, the time-dependent field will cause the potential to rotate; from the time average view, the potential will have a minimal point, and the ion will be confined.

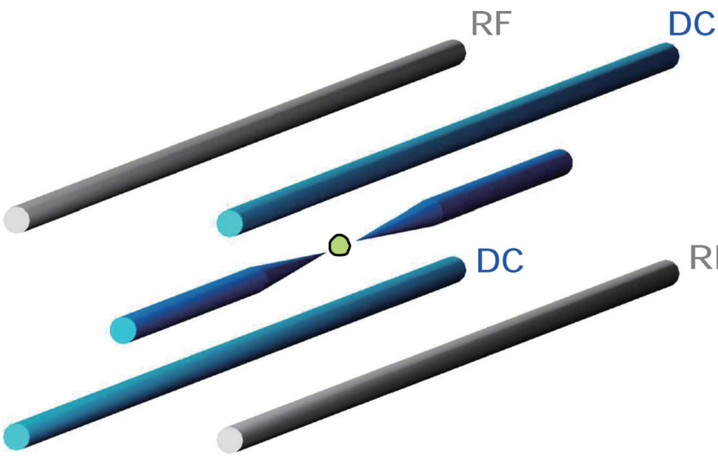

Figure 2. The setup of a typical ion trap. There are five poles in total, two of which are connected to a radio-frequency (RF) current and the others to a direct current.

opposite lasers and scan the detuning slowly, the velocity of the atoms along the direction of the light will be reduced. If six lasers are set along the x, y and z directions, the momentum in all of the directions will be reduced, and the temperature of the atoms will be lower.

There is a Doppler cooling limit, which is caused by the recoil energy of the ion when it emits a photon. The lower limit of the temperature using Doppler cooling is given by $T_{\mathrm{Doppler}} = \frac{h\gamma}{2k_B}$, where h is Planck's constant, γ is the natural line width of the transit used in the Doppler cooling and k_B is Boltzmann's constant. However, for many applications, such as precise spectroscopic measurements and quantum computation, the ions should be further cooled to a lower temperature (such as the ground state of the system). In precise measurements, an extremely low temperature, which corresponds to the low velocity of the ions, is required to eliminate the Doppler effect. In quantum computation, an extremely low temperature is required to initialize the state to $|+\rangle_1 \cdots |+\rangle_n$ with high fidelity. These requirements call for new cooling techniques.

The Doppler cooling experiments for ions were first independently performed in 1978 by Wineland *et al.* using a Mg^+ ion [11] and Neuhauser *et al.* using a Ba^+ ion [12]. After Doppler cooling, the temperature of this system was low enough to quantize the oscillation of the trapped ions. Therefore, two sets of quantized levels were present in this system: the internal level of the ions (we can define the two isolated levels in each ion to be a qubit in quantum information), which was first observed by Wineland *et al.* [13,14] through a quantum jump, and the quantized oscillation in the trap. The coupling between these two sets of levels will play

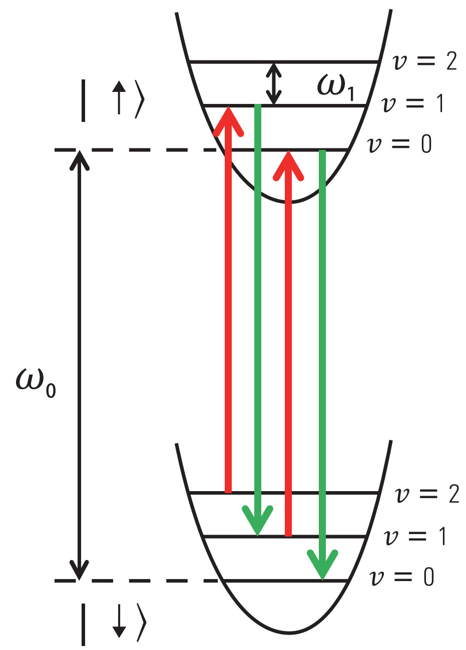

Figure 3. The scheme of sideband cooling (details are provided in the text). Redrawn from figure in [18].

an important role in further cooling and quantum computation.

The coupling between the internal level of an ion and the quantized harmonic oscillator in a trap can be induced by a laser. For simplification, only two related levels (denoted by $|\downarrow\rangle$ and $|\uparrow\rangle$) in the ion and one vibration mode are considered. The interaction can then be described by a simple Hamiltonian under the Lamd–Dicke approximation, a rotating wave approximation and setting of the detuning between the laser frequency and the atom frequency to be the trap frequency [15]:

$$H = \mathrm{i}\hbar\eta(\sigma_- a\dagger + \sigma_+ a), \qquad (4)$$

where σ_+ is the operator $|\uparrow\rangle\langle\downarrow|$ for the ion and $a\dagger$ is the creation operator for the harmonic oscillator. η characterizes the strength of the coupling, which is related to the strength of the laser field and the Lamd–Dicke parameter. This Hamiltonian will play a key role in the further cooling process, i.e. sideband cooling. The sideband cooling technique was developed by Wineland and his colleagues [16,17].

This technique can be used to cool the ion to the lowest energy level by reducing the oscillator of the system to zero. Suppose that the energy gap between the internal state $|\uparrow\rangle$ and $|\downarrow\rangle$ is $\hbar\omega_0$ and that the energy of one oscillator is $\hbar\omega_1$. In sideband cooling processes, a laser with frequency $\omega_0 - \omega_1$ is used in the ion trap system. The ion at the lower internal level, $|\downarrow\rangle$, will be excited to the higher internal level, $|\uparrow\rangle$, by absorbing an oscillator. The excited ion will then decay to the lower state with fewer oscillators. If the processes continue, the ion will eventually be stable at the state without an oscillator. The entire process is similar to the optical pumping processes [19]. The fidelity of the ground state $|\downarrow, 0\rangle$ is dependent on the pumping time.

Wineland and his colleagues [20–22] used well-cooled single ions as optical clocks, which was based on the transition within the optical domain, and dramatically improved the precision of the optical clock (see Fig. 4). The optical frequency is several orders higher than the frequency of a microwave, which is used for the standard Cs clock. However, it is not easy to realize the optical clocks. There are several necessary conditions (which partially overlap the DiVincenzo criteria) for operating them, as noted in previous studies [20–22] and here:

- The ion should have a proper narrow transition and be isolated from the environment.
- The ion in the trap can be cooled to the ground state with the help of a laser through Doppler and sideband cooling. Thus, the Doppler effect resulting from the oscillation can be dramatically depressed.
- The ion can be initialized with high fidelity.
- The state of the ion can be efficiently read out.
- The frequency stabilization technology for the laser is well established.
- A good connection between the radio frequencies and optical frequencies needs to be established.

It is clear that the ion trap is a suitable system for realizing an optical clock and that the sideband cooling technique plays a key role. Wineland and his colleagues realized all of these technologies, and they demonstrated an optical clock based on a single-ion $^{199}Hg^+$ in 2001 [20]. Generally, one ion is used in an optical clock and should satisfy all the former conditions simultaneously. However, in 2005, Wineland and his co-workers demonstrated [21,22] that these conditions can be provided using two different ion species: $^{27}Al^+$ provides the spectroscopy transition and $^{9}Be^+$ provides the cooling transition. The two ions are entangled in the trap, which is called quantum logic spectroscopy. Using these techniques, the precision of the clock can be substantially improved to below 10^{-17}, which is well beyond the former precision. With this extreme precision, these techniques are promising for measuring certain very weak phenomena, such as time dilation, which is predicted by the special relativity theory [24].

Using the DiVincenzo criteria, the ion trap is an ideal system to build a quantum computer. Cirac and Zoller proposed this seminal idea in 1995 [25]. The

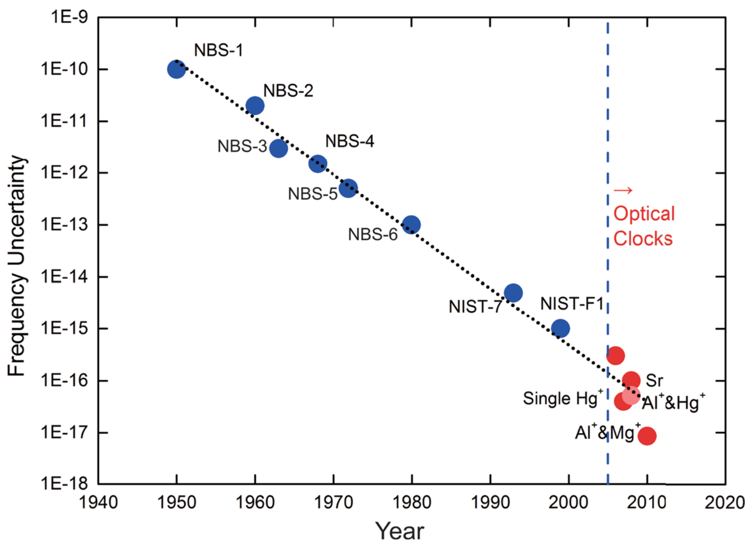

Figure 4. The improvements in the accuracy of atomic clocks. Redrawn from figure in [23].

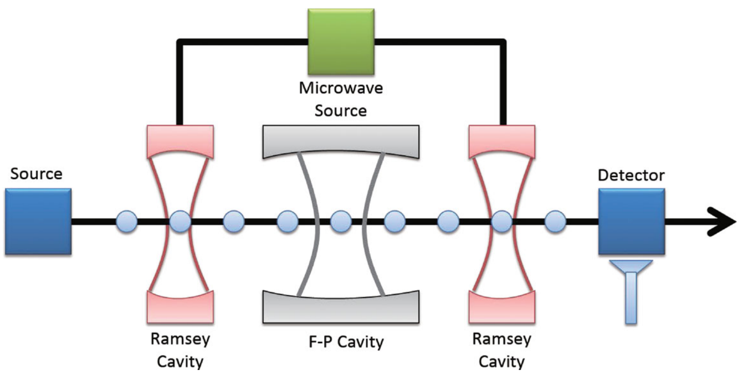

Figure 5. The typical experimental setup of the cavity detected by Rydberg atoms. A typical source is a thermal beam of rubidium atoms, all of which are velocity-selected by laser optical pumping. The Fabry–Perot (F-P) cavity is sandwiched between two Ramsey cavities fed by a classical microwave source, and the state-selective field ionization detector is at the end. Redrawn from figure in [33].

quantum bits (qubits) are encoded into the internal level of the ions, which are well isolated from the environment and can maintain their coherence for a long time. The trapped ions can be aligned in the linear trap and interact with additional coulomb repulsion. The ions will slightly oscillate around the equilibrium points, and the oscillations will induce the phonons in this system. In this system, two types of quantized levels are present: the internal levels of each ion and phonon. The sideband cooling technique is also valid in this situation through the replacement of the oscillators in a single-ion trap by the phonons in a many-ion trap. Using this technique, all of the ions in the trap can be initialized to the ground state without phonons.

The gates in this system can be realized by precisely controlling the interaction between the laser field and the ions. If the frequency of the laser is tuned to ω_0, the frequency difference between the two levels ($|\downarrow\rangle$ and $|\uparrow\rangle$) in an ion, no phonon will be involved in the evolution, and the arbitrary single-qubit unitary operator on that ion can be realized by properly controlling the laser pulse duration. To implement universal computation, we should realize two-qubit gates, such as a CNOT. In this case, we need one phonon to serve as a data bus to transport the information between two ions. Therefore, we tune the frequency of the laser to involve one phonon in the interaction (similar to the interaction in sideband cooling). According to the proposal of Cirac and Zoller, we need another auxiliary level $|r\rangle$ in each ion and another laser to manipulate the interaction between the ground state and the auxiliary level. The auxiliary laser is also tuned to ensure only one phonon is involved in the interaction. The CNOT gate of two ions can be realized through a sequence of these two manipulations [25].

Wineland and his co-workers were the first to experimentally realize the single-ion quantum logic gates and the CNOT gate between different Be^+ ions [26], which demonstrates that the principle of quantum computation in an ion trap is feasible. In 2003, Blatt and his group also achieved the CNOT gate between two Ca^+ ions [27]. It is very hopeful to perform quantum computation in an ion trap after the successful implementation of the CNOT and single-qubit operators in the system.

In addition to the coherent manipulation of the ions in the trap, the scalability of the system is also critical for quantum computation. In 1998, Wineland *et al.* [28,29] first demonstrated the deterministic entanglement between two ions and showed in experiments that information can be distributed in the two ions simultaneously. In 2000, his group then demonstrated the four-ion entanglement experimentally, which proved that the ion trap can be scaled to build a relatively large quantum computer. These experiments demonstrate that the ion trap is the most advanced system to realize quantum computation, and now as many as 14 ions can be well controlled to implement gates [30]. Currently, Wineland *et al.* [31] are focusing on developing technologies to integrate the ions on a chip, which is a very promising approach to scaling up the construction of a practical quantum computer in the future.

There are now several ion trap research groups in China. Two groups are at Tinghua University: Luming Duan's group, which is devoted to implementing quantum computation, and Lijun Wang's group, which is focused on the optical clock. Chuanfeng Li's group at the University of Science and Technology (USTC) is devoted to hybrid ion trap systems with other systems, such as micro-cavity and solid quantum memory, to form a quantum network. Pingxing Chen's group at the National University of Defense Technology is also devoted to quantum manipulations.

MANIPULATION OF A SINGLE PHOTON

Haroche *et al.* focused on confining photons (instead of atoms) in a microwave cavity [32]. The microwave cavity consists of two spherical mirrors that are composed of superconducting material and cooled to the superconductivity phase (see Fig. 5). The photons cannot penetrate the superconducting mirror because of the Meissner effect and thus reflect back into the cavity.

The photon in a high-Q cavity can oscillate for a long time (currently, $\sim$130 ms, corresponding to an extremely high $Q \approx 10^{10}$). With the mode selection character of the cavity, it is possible to study the cavity quantum electrodynamics (CQED) theory. Furthermore, the interaction between the photon and the atom (generally very weak) can potentially reach the strong coupling regime because of the extremely high Q and the small volume of the mode in the cavity. In addition, the photons in the cavity are well isolated from the environment and can maintain the coherence character of the photon field. This system is a good platform for demonstrating the principle of CQED and the fundamentals of quantum mechanics.

The photons (or the non-classical optical field) in the microwave cavity can be detected by a Rydberg atom. Rydberg atoms have very large radii ($\sim$125 nm) and strong coupling to the field. The atoms are prepared with a very high quantum number, such as $n = 50$, $l = |m| = 49$. The transition frequency between $n = 50$ and $n = 51$ is a microwave frequency that is approximately the same as the frequency of the photon in the cavity.

The atoms and photons in the cavity are a good platform to test the fundamental principles of quantum mechanics. QED demonstrates that the spontaneous emission rate of an atom is modified by the spectrum of the vacuum field around it. The vacuum field in a cavity can be strongly modified; thus, the emission of the atom in the cavity can be enhanced or suppressed. In 1983, Haroche and his group [34] first verified the enhancement of the emission rate of a single Rydberg atom in a microwave cavity, which is well supported by QED. The enhancement of the emission rate in a microwave cavity led to the study of light amplification in a cavity, which may be induced to produce new types of masers (or lasers, depending on their frequency). Haroche and his co-workers developed a two-photon maser in 1987 [35,36]. In their maser, the stimulated Rydberg atoms emit two photons simultaneously in a high-Q cavity. The suppression of the spontaneous emission in the cavity within the microwave frequency domain was later independently verified by Kleppner's group (in 1985) [37], Haroche's group (in 1987) [38] and De Martini *et al.* (in 1987) [39]. Moreover, the suppression of the spontaneous atomic emission in a micro-cavity within the optical frequency domain was first demonstrated by Haroche and his collaborators in the early 1990s [40].

Entanglement is a key resource in exploring further fundamental principles of quantum mechanics (such as decoherence processes) and quantum information. Haroche and his co-workers have realized entanglement between atoms and photons using various schemes [41–45] in recent decades. In 1997, Haroche's group [45] prepared an entangled EPR [46] state between two massive particles (here, atoms) with a distance of $\sim$1 cm by exchanging a single photon in a high-Q cavity. These results demonstrate that the quantum information processes between atoms and photons, and atoms and atoms, can be realized experimentally.

Remarkably, an atom can entangle with a mesoscopic coherent field. In 1997, Haroche *et al.* [47] observed the Rabi oscillation of an atom in a very small coherent field (with a few photons) in a cavity with high Q. This type of entanglement is almost the same as the entanglement in a measurement process, i.e. 'atom + measurement apparatus' entanglement. Therefore, it is an ideal platform to investigate the measurement processes. The mesoscopic coherent field can be viewed as the measurement apparatus, and the atom is the observed system. In this entangled state, the pointer of the 'measurement apparatus' is pointed at two bases simultaneously. In the theory proposed by Zurek *et al.*[3], the entanglement between the atom and the measurement apparatus will be destroyed by decoherence processes, and the superposition state will be transformed into a statistical mixture state. The decoherence processes were directly observed in this system by Haroche's group [47]. In 2003, to further investigate the quantum-classical boundary and the decoherence processes, Haroche and his group [48] developed methods to prepare the entangled state between an atom and a larger mesoscopic field with several tens of microwave photons in a cavity with high Q.

In addition, the Rydberg atom can be used as a very sensitive and accurate detector to determine information (number of photons) in the quantum field without destroying the state. The key technique is the quantum non-demolition (QND) measurement [49], which is a very powerful tool used to investigate quantum processes through the quantum state in the cavity. In 1999, Haroche *et al.* [50] realized the first QND measurement for a single photon in an extremely high-Q cavity. In addition, the quantum field in the cavity can be monitored continuously by performing the QND measurement on the field by crossing the atoms through the cavity one by one. Therefore, the quantum processes in the cavity can be observed in real time. In 2007, Haroche *et al.* [33] first continuously observed the single photon in a high-Q cavity and directly observed the creation and annihilation of a photon randomly. The progressive projection of the field into Fock states, with a definite number of photons, has also been observed by the QND measurement. In addition, the quantum jump process was recorded in the cavity [51] using this method. Since 2001, Haroche *et al.* have been devoted to developing and demonstrating new methods to directly measure, with atoms, the phase-space distributions of non-classical fields stored in a cavity (such as the so-called Q and Wigner functions) by combining the QND photon-counting technology with a homodyne mixing method. In 2008, Haroche [52] and his team reconstructed the Fock state and the Schrödinger cat states in a cavity for as many as 12 photons. Using snapshots of the Schrödinger cat states at different times, they were able to create real-time movies of the decoherence process resulting from cavity damping, which clearly demonstrated the transition from quantum to classical in a microscopic system (field in a cavity) coupled to an environment.

With the extremely high-Q cavity, the strong coupling between the field and the Rydberg atoms makes the cavity system an ideal platform for studying quantum information. As previously mentioned, the entangled state can be prepared, and certain quantum gates realized, in this system. Haroche *et al.* [53] realized the conditional quantum phase gate between a Rydberg atom and the field in a cavity, where the field is the controlled qubit (the two levels of the qubit are represented by zero or one photons) and the Rydberg atom is the target qubit. The conditional quantum phase gate makes the transformation

$$\begin{aligned} |0\rangle\,|0\rangle &\to |0\rangle\,|0\rangle \\ |0\rangle\,|1\rangle &\to |0\rangle\,|1\rangle \\ |1\rangle\,|0\rangle &\to |1\rangle\,|0\rangle \\ |1\rangle\,|1\rangle &\to e^{i\phi}\,|1\rangle\,|1\rangle\,. \end{aligned} \tag{5}$$

In addition to the microwave CQED developed by Haroche and his collaborators, Kimble [54] developed the CQED in the optical regime. In the optical regime, the coupling between the atom and the field can reach a strong coupling regime. With the help of the atom cooling and trapping technique, the application of the CQED in the optical frequency domain has been well developed by Kimble's group.

The CQED is a widely used technique today, and many groups in China are working on this system. However, many of these groups are working on micro-cavity systems, which is very convenient for integrating and hybridizing with other systems. Several groups, such as MinXiao's group at Nanjing University and Fangwen Sun's group at USTC, are focusing on constructing a high-Q micro-cavity with SiO_2 materials based on whispering gallery modes. Several other groups, such as Zhiyuan Li's group at the Institute of Physics, CAS, and Jinsong Xia's group at the + Huazhong University of Science and Technology, are focusing on fabricating the micro-cavity in an optical crystal.

CONCLUSIONS AND PERSPECTIVES

With the development of manipulation technologies for atoms (in an ion trap) and photons (in a cavity), we can coherently control several atoms and photons. These technologies can also be used to investigate fundamental quantum mechanics, especially decoherence in the quantum system. Quantum mechanics makes it possible to develop new technologies, such as quantum information, quantum computation and quantum metrology, that will change our classical world. In addition, these new technologies provide new methods for exploring the nature of the quantum world (see Fig. 6).

One example of this exploration is research on the nature of microscopic particles (photon). Using the coherent control of the 'device (beam splitter)', Li *et al.* [55] observed the superposition of the wave and particle state of photons, which also enriched our knowledge of Bohr's complementary principle. In addition, Li *et al.* [4] demonstrated that

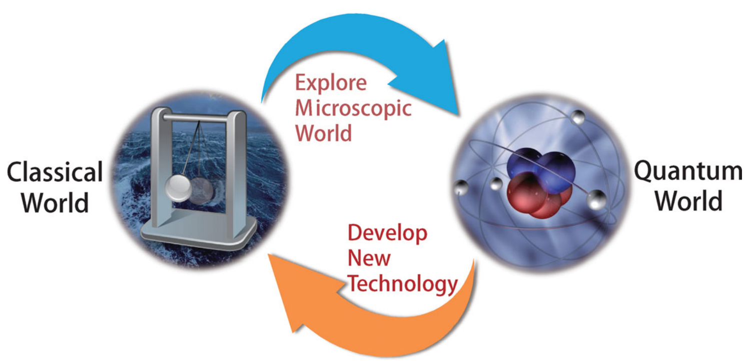

Figure 6. The relationships between fundamental quantum mechanics and the technology of the classical world.

using quantum information technology, the environment of a quantum system can be manipulated to be Markovian or non-Markovian. Furthermore, the current quantum technologies are promising in the investigation of more ambitious problems, such as the interaction between gravitation and quantum mechanics [56].

The achievements of Wineland and Haroche open a new epoch of quantum manipulation. People can verify and control individual microscopic particles, not only as a means for understanding the microscopic world but also to develop new technology in our classical world. However, coherently controlling a large number of microscopic particles remains a considerable challenge and is important in displaying the power of quantum computation. New ideas and new technologies need to be introduced. One of the possible ways of achieving this goal is to integrate the microscopic system on a chip; Haroche and Wineland are currently focused on this path. Another approach involves integrating the cavity (ion trap) system with other systems such as a superconductivity system.

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