

Atomic Structure In Quantum Computing: Enhancing Qubit Coherence Using Atomic Properties

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Quantum computing uses quantum bits (qubits) that take advantage of quantum mechanical effects like superposition and entanglement to do calculations that classical computers can't. One of the biggest problems with quantum computing is keeping qubit coherence, which is the ability of a qubit to keep its quantum state over time. Atomic systems, including neutral atoms, trapped ions, and atomic spin states, present promising solutions owing to their inherent quantum stability and precisely defined energy structures. This review looks at how atomic properties like electron spin states, atomic energy levels, isotopic purity, and interactions with electromagnetic fields can make qubit coherence better. The paper talks about different types of atomic qubit platforms, how coherence times are affected, and new technologies that are being developed to make quantum computers that can be used by many people and don't break down.

Keywords: Quantum computing, atomic qubit platforms, building scalable, quantum computers, qubits.

1. Introduction

Quantum computing is one of the most important technological advances of the twenty-first century. It promises to change the way computers work by using the principles of quantum mechanics. Quantum computers use quantum bits (qubits) that can be in more than one state at the same time because of the principle of superposition. This is different from classical computers, which use binary bits that can only be 0 or 1. Also, qubits can get entangled, which means that the state of one qubit can depend on the state of another qubit even if they are far apart. Because of these features, quantum computers can solve some hard problems, like cryptography, optimization, and molecular simulations, faster than classical computers (Nielsen & Chuang, 2010).

Even though quantum computers have a lot of potential, making them work well is very hard, and one of the biggest problems is qubit coherence. Coherence is the ability of a quantum system to keep its quantum state stable even when it interacts with things around it. Decoherence happens when a qubit interacts with outside noise, thermal changes, or electromagnetic disturbances. This causes quantum information to be lost and computational errors to happen. Consequently, prolonging the coherence time of qubits is crucial for the

development of dependable and scalable quantum computing systems (Ladd et al., 2010). Atomic systems have garnered significant interest as viable candidates for achieving stable qubits due to their precisely defined and inherently stable quantum states. The structure of atoms, which has separate energy levels and intrinsic spin properties, is a good physical basis for storing quantum information. Quantum mechanical interactions between electrons and the atomic nucleus determine atomic energy levels. These interactions create very stable states that can be changed with laser fields or electromagnetic traps. These characteristics render atoms optimal substrates for the fabrication of qubits characterized by extended coherence times and elevated operational fidelity (Wineland & Blatt, 2008).

There have been many proposals and experiments with atomic-based quantum computing architectures, such as trapped ions, neutral atoms, and atomic spin systems in solid-state materials. In trapped ion systems, electromagnetic fields keep individual ions from moving and laser pulses control them, which makes it possible to change quantum states with great accuracy. Another scalable method is to use optical lattices or optical tweezers to trap neutral atoms. This lets you arrange and control large groups of identical atoms to do quantum operations. Also, atomic impurities that are part of semiconductor materials, like phosphorus atoms in silicon, can work as qubits because of their electron or nuclear spin states (Saffman, Walker, & Mølmer, 2010).

The atomic structure is very important for figuring out how coherent these quantum systems are. The stability and lifetime of quantum states are directly affected by things like electron spin, hyperfine interactions, isotopic composition, and coupling with outside electromagnetic fields. Researchers have been able to greatly improve qubit coherence times by carefully controlling these atomic properties and keeping atoms away from noise in the environment. The performance of atomic qubits has improved even more thanks to better laser cooling, ultra-high vacuum systems, and quantum control techniques. This brings us closer to the goal of building large-scale quantum computers.

This review examines the significance of atomic structure in quantum computing, emphasizing the contribution of atomic properties to the enhancement of qubit coherence. The paper looks at different atomic qubit platforms, how coherence and decoherence work, and new technologies that have been developed to make quantum computing systems more stable and scalable.

2. Atomic Structure and Quantum States

Atomic structure is the basic framework for understanding how matter behaves on a small scale and is very important for the growth of quantum computing technologies. A dense central nucleus with protons and neutrons makes up an atom. Electrons, which are in specific energy levels, surround the nucleus. Quantum mechanics posits that electrons do not traverse fixed circular trajectories as proposed by initial atomic models; rather, they inhabit probabilistic regions known as orbitals. These orbitals show how likely it is to find an electron in a certain area around the nucleus. The energies of these orbitals are quantized, which means that electrons can only be in certain energy states and not in a continuous range of energies. A set of quantum numbers describes how electrons are arranged and how they move around in an atom. The principal quantum number (n) tells you what the main energy level is, the

azimuthal quantum number (l) tells you what the orbital's shape is, the magnetic quantum number (m) tells you what the orbital's orientation in space is, and the spin quantum number (s) tells you what the electron's intrinsic angular momentum is. These quantum numbers work together to tell you how an atom's electrons are arranged and how they interact with other particles and electromagnetic fields. These electron spin and energy states can be used to make quantum bits, or qubits, which store and process quantum information (Nielsen & Chuang, 2010).

Superposition is one of the most important ideas that goes along with quantum states. In quantum mechanics, a particle like an electron can be in more than one state at the same time until a measurement is made. This property lets qubits show both logical states 0 and 1 at the same time, which is a big advantage over classical bits, which can only show one state at a time. Quantum entanglement is another important idea. It happens when the quantum states of two or more particles become linked in such a way that the state of one particle directly affects the state of another, no matter how far apart they are. These characteristics constitute the basis of quantum information processing (Ladd et al., 2010).

Atomic systems also show hyperfine interactions, which happen when the magnetic moments of the atomic nucleus and its electrons interact with each other. These interactions make energy level differences that are very stable and precise, which can be used to store quantum information. Atomic systems are great for making qubits with long coherence times because laser pulses or microwave radiation can be used to control these energy transitions very precisely. This kind of stability is necessary to keep quantum information safe and to do quantum operations that are reliable (Saffman et al., 2010).

The principles of atomic structure and quantum states constitute the theoretical foundation of quantum computing. Atomic systems are great for developing stable and efficient quantum technologies because they have separate energy levels, electron spin states, and quantum transitions that can be controlled.

3. Qubit Coherence and Decoherence

In quantum computing, qubit coherence is a key idea that tells us how long a quantum system can keep its quantum state while it is working. Bits in classical computing can only be in one of two states: 0 or 1. Quantum computing, on the other hand, uses quantum bits (qubits), which can be in a superposition of both states at the same time. Coherence is the ability of qubits to keep this superposition and other quantum properties, like entanglement. Maintaining coherence is essential because quantum algorithms necessitate a sequence of operations to be executed prior to the collapse of quantum information into a classical state (Nielsen & Chuang, 2010).

Two important numbers, the relaxation time (T_1) and the dephasing time (T_2), are used to describe coherence in a quantum system. The relaxation time, T_1 , is the amount of time it takes for a qubit to lose energy and go from an excited quantum state to its ground state. The dephasing time, T_2 , is the time it takes for the relative phase between quantum states to stay the same. Both of these factors are very important for figuring out how long a quantum processor can store and work with quantum information. Longer coherence times let you do more steps in a computation and make quantum operations more reliable (Ladd et al., 2010).

But qubits are very sensitive to things that happen in their environment. The delicate quantum state of the qubit can be disturbed by anything that interacts with it from the outside, like electromagnetic fields, changes in temperature, or particles that are close by. This is called decoherence, and it causes quantum information to slowly disappear. Decoherence makes the quantum system act like a classical system, which takes away the benefits of quantum computing. Even small changes in the environment can cause noise that messes up superposition and entanglement.

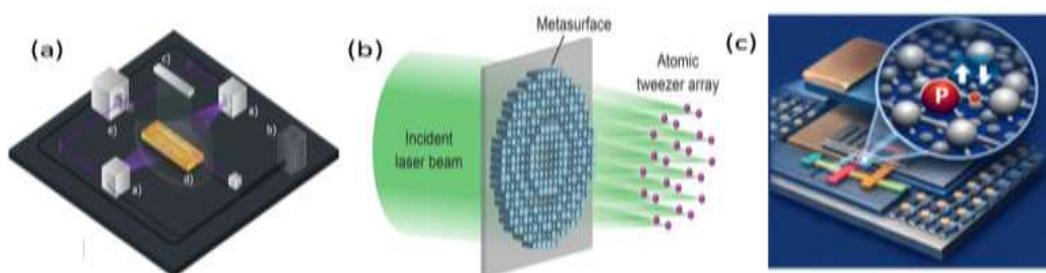
There are a number of things that can cause decoherence in quantum systems. Environmental noise is a big problem. It can come from nearby electronic devices or thermal radiation. Another reason is flaws in the materials, especially in solid-state quantum devices, where flaws in the crystal lattice can affect qubits and cause unwanted energy changes. Also, if not carefully controlled, interactions between qubits can sometimes cause errors. These sources of decoherence restrict the efficacy and scalability of contemporary quantum computing technologies (Devoret & Schoelkopf, 2013).

Researchers are working hard to find ways to lower decoherence and make qubit coherence times longer. Quantum error correction, cryogenic cooling, electromagnetic shielding, and better material engineering are all ways to keep qubits safe from outside forces. Atomic systems, such as trapped ions and neutral atoms, are especially promising because their energy levels are well-defined and they don't interact much with their surroundings, which lets them stay coherent for longer. One of the most important goals of quantum computing research is to make coherence better. This is because longer coherence times will allow for more complex and reliable quantum computations.

4. Atomic Qubit Platforms

Atomic qubit platforms use single atoms or ions to store and change quantum information. Trapped ions, neutral atoms in optical lattices, and atomic spin qubits in semiconductors are all common ways to do this. These systems have high stability, the same quantum properties, and long coherence times, which makes them good candidates for scalable and reliable quantum computing technologies (Saffman et al., 2010).

Fig. : (a) Trapped ion (b) natural atom arrays (c) spin qubits in silicon



4.1 Trapped Ion Qubits

Trapped ion qubits are one of the most advanced and well-developed physical platforms used in quantum computing. This method uses electromagnetic fields created by devices called ion traps to keep individual ions, which are atoms that have lost or gained one or more electrons and are therefore electrically charged, in a small area. These traps, which are usually based on radio-frequency electric fields, keep the ions in a stable position in an ultra-high vacuum environment. Then, the ions' internal electronic states are used to show the two logical states of a qubit, which are usually written as $|0\rangle$ and $|1\rangle$ (Nielsen & Chuang, 2010). Highly controlled laser pulses are used to do quantum operations in trapped ion systems. These lasers change the energy levels of the ions, which lets scientists change their quantum states and use quantum logic gates. Also, the ions can interact with each other because they are all vibrating in the same way in the trap. This interaction makes quantum entanglement possible, which is needed to do complicated quantum calculations. Trapped ion systems have shown very high gate fidelities and reliable quantum operations because these operations can be controlled with very high precision (Wineland & Blatt, 2008).

One of the best things about trapped ion qubits is that they can stay coherent for a long time. The ions are well protected from outside interference, which lets them keep their quantum states for longer than many other qubit technologies. This stability makes trapped ion systems great for experiments that need precise quantum control and error correction.

Trapped ion quantum computers have these benefits, but they have problems with scalability. It gets harder to control and deal with each ion separately as the number of ions in a single trap goes up. However, research is still going on to find better ways to trap ions and make architectures that can be scaled up. This makes trapped ion qubits a top choice for building real quantum computers.

Table: Major Atomic Qubit Platforms Used in Quantum Computing

| Atomic Qubit Platform | Physical System | Qubit Representation | Control Method | Advantages | Limitations | Example Organizations / Experiments |
|-----------------------|---|------------------------------------|---------------------------------------|--|---|-------------------------------------|
| Trapped Ion Qubits | Single ions confined in electromagnetic traps | Internal electronic states of ions | Laser pulses manipulate energy levels | Very high fidelity, long coherence time, well-understood physics | Scaling to large numbers is technically complex | IonQ, University of Innsbruck |

| | | | | | | |
|-------------------------------|---|----------------------------------|---|---|--|--|
| Neutral Atom Qubits | Neutral atoms trapped in optical tweezers or lattices | Hyperfine energy states of atoms | Laser excitation and Rydberg interactions | Highly scalable arrays, flexible geometry | Sensitive to environmental noise | QuEra Computing, Pasqal |
| Atomic Spin Qubits in Silicon | Individual electron or nuclear spins in silicon | Spin-up and spin-down states | Microwave pulses and magnetic fields | Compatible with semiconductor manufacturing | Requires extremely low temperatures | Intel, Silicon Quantum Computing |
| Rydberg Atom Qubits | Atoms excited to very high energy (Rydberg) states | Rydberg excitation levels | Laser excitation controlling strong dipole interactions | Fast quantum gates and strong interactions | Shorter coherence compared with some other systems | Harvard University quantum research groups |
| Optical Lattice Atom Qubits | Atoms arranged in periodic optical lattice traps | Hyperfine atomic states | Laser manipulation in lattice potentials | Naturally forms large 2D or 3D arrays | Individual qubit addressing can be difficult | Max Planck Society laboratories |

4.2 Neutral Atom Qubits

Neutral atom qubits are a good choice for quantum computing because they are very stable, can be easily scaled up or down, and can be controlled very precisely. In this method, individual neutral atoms are held in place and moved around using highly focused laser beams called optical tweezers or put into periodic structures called optical lattices. These atoms don't have a net electric charge like trapped ion systems do, which makes it less likely that they will interact with outside electromagnetic fields. Because of this, neutral atoms can hold stable quantum states for a long time, which makes them good for storing and processing quantum information (Saffman, Walker, & Mølmer, 2010).

In quantum systems with neutral atoms, qubits are usually stored in the atoms' electronic energy levels or hyperfine states. These states are the logical quantum states $|0\rangle$ and $|1\rangle$. Researchers can do quantum operations like single-qubit rotations and two-qubit gates by using laser pulses to change these states. The Rydberg excitation process is one of the most important ways to make neutral atom qubits interact with each other. In this process, atoms are put into high-energy states called Rydberg states, where the outer electron moves a long way from the nucleus. These excited atoms interact strongly with nearby atoms, which makes it possible to control the entanglement between qubits.

One of the best things about neutral atom qubits is that they can be scaled up to work on a large scale. You can use optical tweezers to put thousands of atoms in very organized arrays, which makes big quantum registers. Because atoms of the same element have the same quantum properties, neutral atom systems make qubits that are very uniform. This makes it easier to design quantum circuits and makes operations more consistent.

But there are also some technical problems with quantum computing with neutral atoms. To keep atomic trapping stable and cut down on environmental noise, you need precise laser control and ultra-high vacuum conditions. Also, researchers are still working on making quantum gates with high fidelity. Even with these problems, recent progress in quantum control and optical trapping technologies has made neutral atom platforms work much better. This makes them one of the best options for scalable quantum computing systems.

4.3 Atomic Spin Qubits in Silicon

Atomic spin qubits in silicon are a significant method in solid-state quantum computing, merging the stability of atomic systems with the established technology of semiconductor electronics. In this platform, single atoms, usually phosphorus donors, are placed in a silicon crystal lattice. The spin state of the electron or nucleus that is connected to the donor atom holds the quantum information. These spin states can stand for the two logical states of a qubit, which are usually written as $|0\rangle$ and $|1\rangle$ (Kane, 1998).

There are many benefits to using silicon as a host material for quantum computing. Silicon technology is already used in many classical semiconductor devices. This means that the methods used to make microelectronics could also be used to make quantum processors. Also, isotopically purified silicon, especially silicon-28, has very few nuclear spins. This greatly cuts down on magnetic noise in the system, which lets the donor atom's electron spin stay coherent for longer periods of time (Zwanenburg et al., 2013).

Microwave or radio-frequency pulses are usually used to change the orientation of the electron or nuclear spin in silicon atomic spin qubits. Researchers can use these controlled operations to make quantum logic gates and read the quantum state of the qubit. Experiments have shown that silicon-based spin qubits can stay coherent for a very long time, sometimes even milliseconds or longer. This is very promising for processing quantum information.

Silicon-based atomic qubits are also good because they can work with device architectures that can be expanded. It may be possible to put arrays of donor atoms into semiconductor chips, which would make it possible to build large quantum processors. But making and controlling single-atom devices with atomic accuracy is still a technical challenge. To make sure that quantum behavior is stable, researchers have to carefully place individual atoms and keep the temperatures very low.

Even with these problems, atomic spin qubits in silicon are still a very promising base for future quantum technologies. They are a good choice for scalable quantum computing systems because they have long coherence times, can be made with semiconductors, and could work with classical electronics.

5. Atomic Properties That Enhance Qubit Coherence

Atomic properties like stable energy levels, well-defined electron and nuclear spin states, isotopic purity, and weak interaction with the environment help keep qubits coherent. These traits cut down on environmental noise and decoherence, which keeps quantum states stable for longer periods of time. This makes quantum computing systems more reliable and better at what they do (Ladd et al., 2010).

5.1 Isolation from Environmental Noise

One of the most important things to do to keep qubit coherence in quantum computing systems is to keep them away from noise from the outside world. Quantum states are very fragile and can be easily disturbed by things that happen around them. Electromagnetic radiation, temperature changes, vibrations, and collisions with nearby particles are all outside factors that can change the quantum state of a qubit. These disturbances cause unwanted changes in energy and phase shifts, which cause decoherence. This makes the qubit lose its quantum information and act like a classical system.

To reduce these disturbances, quantum systems, especially atomic qubits, are usually run in very controlled settings. For instance, a lot of quantum computing tests are done in ultra-high vacuum chambers, which get rid of most of the particles in the area around them and lower the number of collisions with atoms or ions. Also, cryogenic cooling methods are often used to bring the system's temperature down to very low levels. When temperatures drop, thermal vibrations and electromagnetic noise go down, which helps keep quantum states stable. Another important way to keep qubits safe from outside interference is through electromagnetic shielding. Carefully designed shielding materials keep stray electric and magnetic fields from affecting the quantum system. In atomic-based quantum computing platforms, like trapped ions or neutral atoms, these methods of isolating qubits greatly increase their coherence time.

Researchers can keep quantum superposition and entanglement for longer periods of time by effectively isolating qubits from noise in the environment. This makes quantum computations more reliable.

5.2 Identical Quantum Structure

One of the best things about atomic systems in quantum computing is that they have the same quantum structure. Atoms that are the same element and isotope have the same internal properties, such as energy levels, electron configurations, and spin states. This uniformity comes from the basic rules of quantum mechanics, which say that all atoms with the same number of protons, neutrons, and electrons act the same way. Because of this, atomic qubits show quantum behavior that is very predictable and can be repeated. This is important for making quantum computing systems that work well (Nielsen & Chuang, 2010). In quantum computing, qubits have to do things with very high accuracy. If different qubits behave slightly differently because of differences in their physical properties, it can cause errors in calculations and make quantum algorithms less reliable. Atomic systems naturally avoid this problem because their internal structures are always the same. For instance, in quantum platforms with neutral atoms or trapped ions, all of the atoms have the same quantized

energy levels and respond the same way to laser or electromagnetic control fields. This consistency makes it easier to control and change large groups of qubits.

Another important benefit of identical quantum structure is that it makes things easier to scale. When thousands of atomic qubits are put together in optical lattices or ion traps, they can work together without needing to be calibrated separately for each qubit because they all have the same properties. This makes experiments easier and makes quantum operations work better overall.

Also, identical quantum systems help keep coherence because they keep the differences in energy levels between qubits to a minimum. Less variability means that unwanted interactions or phase errors are less likely to happen, which keeps quantum states stable for longer periods of time. Because atoms have the same quantum structure, they are a great base for building scalable and high-fidelity quantum computing architectures.

5.3 Weak Interaction with Environment

A weak interaction with the environment is an important trait that helps atomic quantum systems improve the coherence of their qubits. For quantum computers to work, qubits need to stay in fragile quantum states like superposition and entanglement for a while. Nonetheless, interactions with external particles, electromagnetic fields, or thermal energy can disrupt these states and induce decoherence. Consequently, systems that inherently exhibit reduced interaction with their environment are more adept at preserving stable quantum information (Ladd et al., 2010).

Atomic qubits are especially useful because many of their internal states, like electron spin or nuclear spin states, don't interact much with outside forces. For instance, surrounding electrons often protect nuclear spin states from changes in the magnetic field outside of them. This natural shielding keeps the quantum state stable for longer periods of time, which increases the qubit's coherence time.

Also, quantum computers usually use advanced experimental methods like ultra-high vacuum environments and laser cooling to keep atomic systems separate. These methods greatly cut down on collisions with nearby particles and thermal motion, which makes interactions with the environment even less likely. Because of this, atomic qubits can keep their quantum properties for longer periods of time than many other physical systems. So, the weak interaction between atomic qubits and their surroundings is a key factor that makes quantum operations possible. Researchers can better protect quantum information by reducing environmental noise. This lets them do more complicated quantum calculations before decoherence happens.

5.4 Isotopic Purification

Isotopic purification is a key method for improving qubit coherence in quantum computing systems, especially in solid-state platforms like silicon-based quantum devices. Atoms of the same element that have the same number of protons but different numbers of neutrons in their nuclei are called isotopes. Although these isotopes exhibit analogous chemical properties, their nuclear spin characteristics may differ considerably, potentially affecting the behavior of adjacent quantum states (Zwanenburg et al., 2013).

In many materials, naturally occurring isotopes have nuclei that have a nuclear spin that is not zero. These nuclear spins make the material's magnetic fields change, which can mess with qubits and add noise to the quantum system. These kinds of magnetic fluctuations can mess up the delicate superposition states of qubits and cause decoherence. If there are a lot of spin-active isotopes in the surrounding material, the coherence time of qubits may be shorter. Isotopic purification solves this problem by taking out isotopes with nuclear spin and adding isotopes with no nuclear spin to the material. Silicon-28 is a well-known example of an isotope of silicon that doesn't have nuclear spin. When silicon is cleaned up so that it mostly contains silicon-28, the magnetic noise in the material goes down a lot. This lets electron or nuclear spin qubits that are built into the silicon lattice keep their quantum states for much longer.

Isotopically purified materials have been shown in experiments to greatly improve qubit coherence times, sometimes by several orders of magnitude. This enhancement renders isotopic purification a formidable approach for the advancement of more stable and dependable quantum devices. Isotopic purification helps make the quantum environment cleaner by reducing internal sources of magnetic noise. This makes it easier to store and manipulate quantum information with more accuracy.

6. Challenges and Limitations

1. Scalability Issues

Expanding atomic quantum systems to thousands or millions of qubits remains technically challenging. Controlling and addressing each qubit individually becomes more complex as the system size increases.

2. Environmental Sensitivity

Quantum systems are highly sensitive to external disturbances such as electromagnetic noise, temperature fluctuations, and vibrations, which can lead to decoherence and loss of quantum information.

3. Complex Experimental Setup

Atomic quantum computing platforms require sophisticated equipment such as ultra-high vacuum chambers, laser cooling systems, and precise electromagnetic control, making experiments expensive and technically demanding.

4. Gate Operation Speed

In some atomic qubit systems, quantum gate operations can be slower compared to other platforms like superconducting qubits, which may limit computational speed.

5. Error Accumulation

Even small operational errors during quantum gate operations can accumulate over time, reducing the accuracy of quantum computations and requiring advanced quantum error correction techniques.

6. Precision in Atomic Placement

For systems like atomic spin qubits in silicon, placing individual atoms with atomic-level precision is extremely difficult and requires advanced nanofabrication techniques.

7. Readout and Measurement Challenges

Measuring the quantum state of qubits without disturbing the system is complex and requires highly sensitive detection methods.

8. Temperature Requirements

Many quantum systems must operate at extremely low temperatures using cryogenic cooling to maintain stable quantum states, which increases the cost and complexity of quantum hardware.

7. Conclusion

The structure of atoms is a strong and dependable base for the growth of quantum computing technologies. Atoms can be very stable quantum bits (qubits) because they have discrete energy levels, well-defined electron and nuclear spin states, and quantum transitions that can be controlled. These atomic properties enable fundamental quantum phenomena like superposition and entanglement, allowing quantum computers to execute intricate calculations that surpass the capabilities of classical systems. Because of this, atomic-based platforms like trapped ions, neutral atoms, and atomic spin qubits in silicon are now at the heart of quantum computing research.

One of the best things about atomic qubits is that they can keep their coherence times for a long time. Identical quantum structure, weak interaction with the environment, and isotopic purification are some of the properties that greatly lower noise and disturbances that cause decoherence. Laser cooling, ultra-high vacuum trapping, and precise electromagnetic control are some of the most advanced methods that make atomic quantum systems even more stable. With these methods, scientists can change and keep quantum states very accurately. Even with these benefits, there are still a number of problems that need to be solved before quantum computing can be used on a large scale. We still need to deal with problems like scalability, complicated experimental setups, and sensitivity to the environment. Still, atomic qubits keep getting better thanks to ongoing research in quantum engineering, materials science, and error correction methods. Atomic systems are expected to be very important in the future development of scalable and fault-tolerant quantum computers as research and technology continue to improve.

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