Several Ways to Implement Qubits in Physics

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Abstract. In order to achieve quantum computation, the qubit preparation is crucial, given that the performance relies on various gate operations, which is determined by the quality of qubit. This paper introduces many qubits, including atoms (neutral atoms and ions) and spins (quantum dots, diamond NV centers, and nuclear magnetic resonance) that depend on various systems. Moreover, they are mentioned separately in this paper due to the significance of superconducting qubits. Meanwhile, the advantages and drawbacks of these qubits are compared, e.g. their coherence (long coherence time between neutral atoms and ions), operating temperature, quantum state reading, quantum system ease of handling, and precision of handling. Challenges as well as corresponding resolved methods have been addressed and reviewed. Current gaps and limitations are also discussed.

Keywords: Qubit, Quantum computation, Quantum dots, Diamond NV center, NMR, Superconducting.

1. Introduction
After quantum computing was proposed, the physical realization of qubits has been an important problem that hinders the development of quantum computing. Although numerous studies have been conducted to study atomic photonic electrons, combining them and realizing the qubit system with strong controllability and coherence are unsolved issues. Fortunately, researchers have come up with a number of potential quantum systems with which they have done some quantum computing. However, these methods vary widely, often using different physical systems and different techniques for manipulating and reading and reading. Neutral atoms [1, 2] and ions [3] are atomic-type qubits, while diamond NV centers, nuclear magnetic resonance, and quantum dots are spin types. Another type of superconducting qubits has been produced and studied in commercial companies. These types of qubits cover the current research of researchers on qubits, in general. Some of these qubit systems are entirely new, some rely on previous research on other qubit systems, and others have discovered properties that can be used in quantum computing. These quantum systems appear to be very promising, but in this paper we want to focus on what has been achieved in practice rather than what can be predicted in theory.

In this paper, issues like how quantum systems can be manipulated and how to reduce their decoherence will be further explored, as well as experimental validation of these methods. In addition, for spin qubits, a new quantum system [4], called NER, has recently been proposed at the end of the NMR chapter, which will be discussed as well.
2. Atomic Quibits
For several years, the research of the atomic system has been continued to be debatable topic in the field. As a well-developed qubit, atomic quibits is considered to be a promising quantum technology system in the near future.

2.1. Neutral Atoms
Atoms have several levels of energy, some of which are very stable, and have been widely studied in the last century. They can be cooled to nK temperatures and captured in microscopic arrays generated by laser beams called optical lattices. Atomic capture and manipulation can be done with high precision. The contrast of qubit rotation on a single atom is 99% [1, 2]. It is currently difficult to independently work and calculate neutral atoms in optical lattices, although a lot of research has been done on the separate addressing and reading of neutral atoms.

Since the atom itself is relatively stable and has a poor interaction with the outside world, it is considered to be an excellent quantum information storage device, and it is possible to use the atomic ensemble to capture and manipulate photons states [5]. Figure 1 displays an image of atomic qubits. Neutral ultra-cooled atoms in optical lattices could be controlled by using lasers to trap them in microscopic arrays, which can be precisely manipulated for final use [6]. Similarly, an electric field can also be used to manipulate neutral atoms [7].

However, the interaction between neutral atoms is relatively weak due to the above characteristics, and it is difficult to generate stable and controllable quantum logic gates, but this problem is already under study [8-10]. Rydberg-blockade interactions are based on one of the two-qubit entanglement gates. Optical pumping is done with qubit initialization and qubit reading is based on resonance fluorescence imaging. This method’s fidelity is very high and tolerant. Using spin interactions, a team of researchers has successfully created two-qubit SWAP gate [11].

![Figure 1](image1.png)

**Figure 1.** Atoms trapped in an optical lattice: (a) The principle of trapping neutral atoms in periodic optical potential is illustrated; at each lattice location, one neutral atom qubit is trapped; (b) shows one potential mechanism for creating multi-particle entanglement starting with two atoms in separate spin states, trapped in each lattice site [12].

In recent years, the construction of qubits by neutral atoms has been proposed and realized, but the difficulty of generating entanglement logic gates is still an issue that can not be ignored. At the same time, there is a very weak interaction between neutral atoms and the atmosphere that protects them against decoherence.

2.2. Ionic quibits
In reality, ions and neutral atoms have a very similar feature, i.e., ions can also be manipulated by electric field, magnetic field, and laser with high precision, and ions have great charging advantages.
The strong interaction with Coulomb will make the interaction between ions very strong, so it is easy to make entanglement logic gates [3].

Ions trapped in electromagnetic fields have been used to encode and manipulate quantum information. Figure 2 shows two ways to trap ions. Using hyperfine structures, people have done a lot of work on the entanglement logic gates between ions. The coherence time of these methods is relatively long and the accuracy is relatively high. The qubits of ions have high fidelity. For the optical qubits stored in 40Ca+, the average readout fidelity of 99.991% is obtained in the experiment. The adaptive measurement technique achieves 99.99% fidelity in the range of average detection time of 145s. For 43 calcium, a long-lived hyperfine qubit is transmitted to optical qubits within 10s, and the theoretical fidelity is 99.95%. 99.87% transmission fidelity and 99.77% net readout fidelity are achieved [13]. Another research team also proved that the loss of coherence of ionic qubits is very small with empirical evidence [14]. As the fluctuating magnetic field is likely to have an impact on ions, a research team has come up with a new solution to this problem [15]. The benefits of ionic qubits and neutral atomic qubits are that entanglement logic gates are easy to control and easier to create, but they are more likely to be influenced by external fields and lead to problems with decoherence. The ionic form does not, however, have an absolutely dominant advantage over the atomic form.

Figure 2. There are many kinds to trap the ions, e.g. (a) a linear trap; (b) a planar trap. [12]

3. Spin qubits
Spin qubits are found in solids, often using electron spins in quantum point semiconductors, or using nuclear spins in centers with nitrogen vacancy (NV). Furthermore, nuclear magnetic resonance is also a common way for nuclear spins to be used.

3.1. Quantum Dots
A quantum dot is a nanoscale structure in which electrons have distinct energy levels and are trapped in a potential well. Either electrostatic defined quantum points, which are regulated by a voltage on a metal gate, or self-assembling quantum dots, which are the artificial potential energy of the growth of a semiconductor, can be generated in several ways. Controlled by electricity or light, qubits have been experimentally manipulated [16]. The coupling between electric fields and individual electron spin in quantum dots is strong, up to 5MHz [17], and therefore receives very little interference.

The combined spin state of two electrons trapped in a double quantum dot structure centered on a sub-micrometer-scale semiconductor can be used as a qubit, as illustrated in Figure 3.
Figure 3. The collective spin state of two electrons trapped in a sub-micrometer-scale semiconductor-based double quantum dot structure can be used as a qubit [12].

There are several price structures with Quantum-dot quantum ratios, one of which blends speed and simplicity of output, and the qubits are highly adjustable. It consists of a double quantum dot on one stage with one electron and on the other with two electrons. This makes it possible to implement single-qubit gates and double qubit gates easily in a simplified geometry and with fewer operations with fast operations proposed for QDS than other qubit architectures. In reality, the system has a potentially lengthy decoherence duration. These are attractive properties for quantum information processing devices [18].

A team has recently proposed a double hybrid qubit coupling scheme based on exchange interaction that is regulated between qubits by quantum tunneling coupling. Controlled Z-gates with a length of 5ns and zero controlled non-gates with a length of 7ns can be achieved with fidelity greater than 99.9% [19]. Solid-state qubits, such as quantum dots, are appealing and can be engineered and assembled into large arrays to have unique properties.

3.2. Diamond NV Center

Figure 4. The diamond NV center [20].
The NV core of a diamond consists of an alternative nitrogen (N) atom that replaces the carbon atom and an adjacent vacancy (V). In such a device, both the electron spin and the nuclear spin may be used for quantum technology, and the coherence time is long. Another big way to use spin is to use the NV core of the diamond. It can be implemented at a higher temperature, which is much better than quantum dot systems. And vice versa, the device at room temperature may also monitor for weak magnetic fields [21], which can then be used for precise measurements. Figure 4 presents an image of the diamond NV center.

Another characteristic of diamond NV centers is that both optical and microwave fields can be coupled to them, so they can be used as interfaces between optical and solid systems. This is critical because this functionality is not available to other forms of qubits. This ability can be used to generate entanglement of remote solid qubits [22], enabling quantum interference of two polarized optical photons generated by the NV center in two separate diamond samples. For a coherent coupling mechanism between distant spin qubits and ferromagnetic dipoles with a corresponding operating time of tens of nanoseconds, a similar method has been proposed [23].

The potential of this type of approach is obvious [24] and has been recognized by researchers, and diamond NV centers have recently become a major candidate for quantum information technologies for long-distance communications due to their unique properties.

Diamond NV centers do not need a high temperature, unlike quantum dots. The former needs to operate at a temperature of several K, while the operation of diamond NV centers requires only room temperature.

3.3. Nuclear Magnetic Resonance

Nuclear magnetic resonance (NMR) technology is commonly used to regulate semiconductor nuclear spin, and it has been shown to be experimentally effective. This technique has a long history and is used to regulate semiconductor nuclear spin. By highlighting the rf pulse, it is possible to realize the general control of high fidelity. In the strongly coupled state, the time scales of the selective qubit. This indicates that solid-state NMR systems tailored for quantum information processing have excellent potential [25, 26]. Phosphorus atoms can also be manipulated by NMR. A typical NMR setup is given in Figure 5.

**Figure 5.** NMR setup. An ensemble of single qubits forms spin-1/2 nuclei of an ensemble of 1015 molecules. The sample usually consists of a few milligrams of an organic compound dissolved in around 0.5ml of an appropriate NMR inactive solvent (in this example, it is chloroform). [27]
NMR systems can also be used to demonstrate quantum state evolution by freezing [28], including separable and maximum entangled states. It is also regarded as one of the two quantum systems closest to industry. Many quantum algorithms have been implemented on it, such as the Deutsch problem [29], Deutsch-Jozsa algorithm optimized version [30]. In addition, an NMR implementation of double qubit quantum gates is proposed by coupling to bystanders to indirectly process quantum information [31].

Because of NMR quantum computation on maturity, several teams have been dedicated to using NMR to understand computer science theory problems, such as algorithm complexity, the most straightforward example is to use a Monte Carlo algorithm to measure the quantum computer theory in quantum computers with the current work under the same energy condition to perform the calculation [32]. Studies have shown that large system size does not become an obstacle to optimal control [33], which further illustrates the superiority of NMR in theory.

NMR technology has allowed unprecedented control of the dynamics of coupled two-level quantum systems for more than 60 years. The dominant factor in the experimental implementation of quantum protocols has been nuclear magnetic resonance. It is very useful for other quantum systems that perform tasks of processing quantum information and is on the path to industrialization.

Recently, scientists have discovered a new quantum system that is similar to nuclear magnetic resonance but uses an electric field to regulate the interaction of the nuclear quadrupole moment with the surrounding gradient electric field [34]. This is thought to be a new way of qubit regulation and has many similarities with nuclear magnetic resonance.

4. Superconducting Qubits

The superconducting qubit circuit, which is based on the Josephson junction, is actually macroscopic. The operating temperature is in the order of tens of mK, and through the Josephson junction, it introduces nonlinearity, rendering the energy level separation non-uniform (if the energy level separation is uniform, then the first two energy levels can not be well distinguished) [35]. This property enables individuals to encode qubits to accomplish quantum computation and simulation at the lowest two energy levels [36, 37]. Quantum information can be encoded in various ways: the island’s number of superconducting electrons, the path of the current around the loop, or the circuit’s oscillating state. Operated with voltage and current applied, the benefit of superconducting circuits over real atoms is that to configure their characteristic frequencies, interaction powers, and so on, they can be built and constructed. In addition, it is possible to pair superconducting circuits with "cavities" that are, in essence, electrical resonators [38]. As can observed from Figure 6, a schematic diagram of an array of superconducting flux qubits is displayed.

![Figure 6. Schematic diagram of an array of superconducting flux qubits. [34]](image)

In fact, superconducting qubits are another kind of quantum system that is expected to have a very long coherence time, often greater than 100s [39], which is large compared to other energy scales in
circuits. Moreover, high fidelity quantum gates based on superconducting qubits have also been greatly developed.

Using superconducting circuits, people have begun to implement quantum algorithms on them, two-bit quantum algorithms have been demonstrated very early [40], and the Bell inequality has been verified [41].

The main limitation of superconducting qubits is that they are very sensitive to decoherence environmental noise. The external electromagnetic field and other factors can be reduced by improving the circuit design [42], but there are still internal low-frequency noises that are hard to avoid, mainly from charge fluctuation. A modified charge qubit (transmon) has been proposed as a complement [43]. This method decreases the dispersion of the charge by a much smaller amount than the anharmonic reduction (needed to prevent qubits from being harmonic oscillators). Because qubits are less sensitive to charge changes, electrostatic gates is becoming unnecessary tuning to the sweet spot of the charge. Furthermore, another modified SC qubit, called Fluxonium, was suggested. A junction is diverged in the flux by a series of major tunnel junctions [42]. By carefully choosing the parameters of the tunnel junction, the flux can be shielded from charge and flux noise.

Although the coherence time of superconducting qubits is shorter than that of other types of qubits (but a long order of magnitude compared to the rest of the time in the circuit), owning to technology advancements, the world record for the coherence time of superconducting qubits has been improving.

5. Conclusions
In the current paper, we introduced six different systems of qubits, including atomic, spin, and superconducting qubits, and explained several technical challenges and the corresponding solutions proposed in previous literature. We provide a thorough analysis exploring the qubits from various aspects: some are with a strong temperature range that can work at room temperature; some have strong coherence and thus can be hardly influenced by ambient noise; some are easier to read out; and some are easier to tamper with. For the realization of quantum computing, the construction of such qubits is important because all computing operations are performed on qubits, and the existence of qubits also decides whether the device is of practical value, e.g. for commercial use or for academic quantum algorithm verification. In the future, the most critical issue in quantum computing is decoherence. Nevertheless, thanks to the efforts of pioneer researchers, qubits are breaking records again and again and we are on the verge of overcoming flipping challenges in quantum computing.

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