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Natural and artificial atoms for quantum computation

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Abstract

Remarkable progress towards realizing quantum computation has been achieved using natural and artificial atoms as qubits. This paper presents a brief overview of the current status of different types of qubits. On the one hand, natural atoms (such as neutral atoms and ions) have long coherence times, and could be stored in large arrays, providing ideal ‘quantum memories’. On the other hand, artificial atoms (such as superconducting circuits or semiconductor quantum dots) have the advantage of custom-designed features and could be used as ‘quantum processing units’. Natural and artificial atoms can be coupled with each other and can also be interfaced with photons for long-distance communications. Hybrid devices made of natural/artificial atoms and photons may provide the next-generation design for quantum computers.

(Some figures in this article are in colour only in the electronic version)

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1. Introduction

The experimental realization of quantum computation (QC) has been a challenge for more than a decade. While a fully operational quantum computer that could factorize thousand-digit numbers is still a distant goal, with the new technologies for the coherent manipulation of atoms, photons and electrons, nowadays applications like quantum cryptography and quantum communication are already commercially available. Since potential QC implementations come in many shapes and sizes, it is difficult to quantify the overall progress in the field of QC. In order to assess the current state of the art in QC, a comparison between the various approaches is needed. However, because these approaches are very different (in terms of the underlying physical processes,

experimental techniques, and how well the physical system is understood), we should be careful not to compare apples with oranges. We would rather like to compare apples with apples, or in our case, atoms with atoms. Therefore, in this paper we consider natural and artificial atoms for implementing QC.

Among the most successful and rapidly developing ways of realizing QC are those using *natural atoms* (such as neutral atoms [1] or ions [2]) and *artificial atoms* (such as superconducting circuits [3, 4] or spins in solids [5]). Contrasting natural and artificial atoms would help in highlighting their strengths. For the sake of comprehensiveness, other QC approaches (i.e. with nuclear spins in molecules [6, 7] or in phosphorus impurities in silicon [8, 9], photons [10, 11] and so on) are also briefly covered here. A complementary overview on qubits can be found in [12].

Although there are many exciting theoretical proposals, we will focus more on what has already been experimentally demonstrated and less on what could eventually be achieved in each system. We should stress from the beginning that our purpose is not to show that a certain system is better than others, but to review the current experimental state of the art in QC. One should also keep in mind that some approaches are more recent than others, some benefit from technologies that have been developed before, while others had to develop their own new technologies on the way, and, most importantly, each approach has to deal with specific issues whose difficulty cannot be compared.

By considering natural and artificial atoms and their potential for implementing QC, we hope to gain a broader perspective of the current status of QC. Moreover, this approach may also provide a glimpse into the future of QC. However, we would rather not attempt to make any prediction regarding what system would be the best for realizing a practical quantum computer. Ten or 20 years from now such speculation might sound as amusing as the prediction made by *Popular Mechanics* in 1949: ‘In the future, computers may weigh no more than 1.5 tonnes.’

After summarizing the characteristics of each system we discuss the strengths and weaknesses of natural and artificial atoms. Next, we take a look at hybrid systems and photon interfaces, and, finally, consider future prospects. The main issues discussed throughout the paper are collected in six tables, which can be found at the end of the paper. For readers interested in the details for a particular system, the appendix provides extended tables. The list of references at the end tries to cover some of the recent experimental progress in the coherent control of natural and artificial atoms.

2. Neutral atoms

When looking for a physical system to realize qubits (which are controllable two-level systems), perhaps the most obvious candidate is neutral atoms [13–38]. Atoms have many energy levels that have been studied extensively over the past century, and some of these energy levels are extremely stable. Indeed, with accuracies better than one part in 10^{-15} , atomic clocks provide the best available time and frequency standards. The qubits encoded in the atomic energy levels can be initialized by optical pumping and laser cooling, manipulated with electromagnetic radiation, and then measured via laser-induced fluorescence. In short, atoms provide clean, well-defined qubits (see also box 2(a) and (b) and table A1).

Neutral atoms make attractive qubit candidates also because of their weak interaction with the environment, leading to long coherence times [14, 15, 19, 30]. They can be cooled down to nK temperatures and trapped in very large numbers (millions) in microscopic arrays created by laser beams (called optical lattices). The trapping and manipulation of atoms can be done with high precision [14, 18, 19, 21]. Until recently, the individual manipulation and measurement of neutral atoms in optical lattices was not possible, but the experiments in [24, 29, 31, 32, 35] show very promising perspectives for individual addressing and readout.

While one-qubit gates can be implemented with very high fidelity [34], realizing two-qubit gates or many-qubit entangled states is challenging because the atoms interact very weakly with each other. This problem can be overcome in several ways. For instance, the atoms can first be brought into a superposition of two internal spin states. Then, as the spin-dependent lattice is moved, the atoms go to the left and to the right simultaneously colliding with their neighbors. In this way, in a single operation, a highly entangled many-qubit state can be created [13]. Unfortunately, these collisional gates are very sensitive to decoherence and are also quite slow [1]. Exchange interactions provide an alternative approach [20, 22, 25]. The effective spin–spin interaction between two atoms in a double-well potential was used to demonstrate a two-qubit SWAP gate [20]. Furthermore, with polar molecules [17] or Rydberg atoms [27, 28, 36] dipole–dipole interactions could be exploited for realizing two-qubit gates. Very recently, a CNOT gate [33], post-selective entanglement of two atoms [37] using Rydberg blockade interactions and on-demand entanglement [38] have been demonstrated.

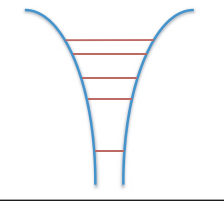
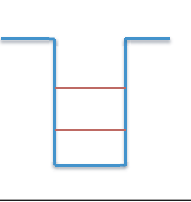
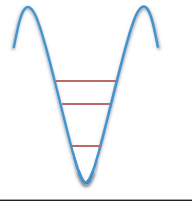

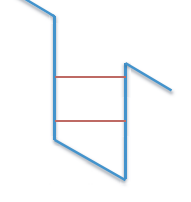
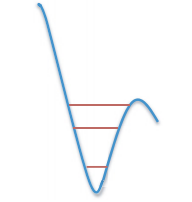
The prospect of producing many-qubit entangled states together with the possibility of single-site addressing and measurement makes neutral atoms promising for the quantum simulation of condensed-matter physics [16, 23] as well as measurement-based QC [39].

3. Ions

While neutral atoms interact weakly among themselves, ions, being charged, interact rather strongly via Coulomb repulsion. This facilitates the implementation of two-qubit gates without compromising the long coherence times [40–64]. Also, thanks to their charge, the motion and position of the ions can be well controlled. Ions can be trapped by electrical (or magnetic) fields, laser-cooled and manipulated with high precision [2]. Quantum information can be encoded either in the internal (hyperfine or Zeeman sublevels, or the ground and excited states of an optical transition), or in the motional states (the collective motion of the ions). While the internal states exhibit very long coherence times (hyperfine transitions >20 s [50] and optical transitions >1 s) the motional states have typical lifetimes of <100 ms. As in the case of neutral atoms, the initialization of the qubits can be done by optical pumping and laser cooling, and they can be measured with very high accuracy [59, 62] via laser-induced fluorescence. Scaling the current experiments to large numbers of ions is theoretically possible, but technically challenging. The proposed approaches to scalability include ion shuttling, two-dimensional ion arrays, photon interconnections, long equally-spaced strings, and two-dimensional Coulomb crystals (see [57] and box 2(c) and (d) and table A2).

Using the collective motion of the ions as data bus, high-fidelity one-, two- [53, 56] and even three-qubit [60] gates have been experimentally demonstrated. Entangled (Greenberger–Horne–Zeilinger (GHZ) and W) states of up to 14 qubits have been realized [51, 52, 64]. Two-qubit gates can also be implemented using bichromatic excitation fields that produce coherent two-qubit transitions [42, 56] or by

Box 1. Natural and artificial atoms.

	Natural atoms	Artificial atoms	
	Atoms and ions	Quantum dots	Josephson junctions
$E = 0$			
$E \neq 0$			

Both natural and artificial atoms exhibit discrete energy levels, which are modified in the presence of external fields ($E \neq 0$). The applied external fields drive coherent quantum oscillations between the specific energy levels which can be used to encode the qubit states. Artificial atoms can be engineered to have certain transition frequencies while in natural atoms these are fixed.

the state-selective displacement of the ions with an optical ‘pushing’ force [41]. In the latter, the displacement changes the strength of the Coulomb repulsion, leading to an additional phase, hence realizing a controlled-phase gate. Recently, a trapped ion quantum processor implementing arbitrary unitary transformations on two qubits has been realized [58].

In addition to the generation of GHZ and W entangled states, quantum algorithms [44, 49], quantum teleportation [46, 48], entanglement of distant qubits [55], quantum error correction [47] and decoherence free qubits [61] have also been demonstrated with trapped ion qubits.

4. Superconducting circuits

Superconducting circuits [65–100] are typically μm -scale circuits operated at mK temperatures. Although macroscopic, they can still exhibit quantum behavior, which can be harnessed for QC [3, 4, 102, 103]. Superconducting circuits are RLC circuits that also include nonlinear elements, called Josephson junctions. Thanks to superconductivity, the resistance vanishes ($R = 0$), eliminating the most serious source of dissipation and noise. Now, the LC circuit is a harmonic oscillator. The problem with harmonic oscillators is that they have an infinite number of equally spaced energy levels and therefore it is not possible to target only the lowest two energy levels. By introducing nonlinearity through the Josephson junction, the energy-level separation becomes nonuniform, and the lowest two levels can be used to encode the qubit [3, 4] (see also box 1). Quantum information can be encoded in different ways: in the number of superconducting electrons on a small island (charge qubit), in the direction of a current around a loop (flux qubit), or in oscillatory states of the circuit (phase qubit). These qubits

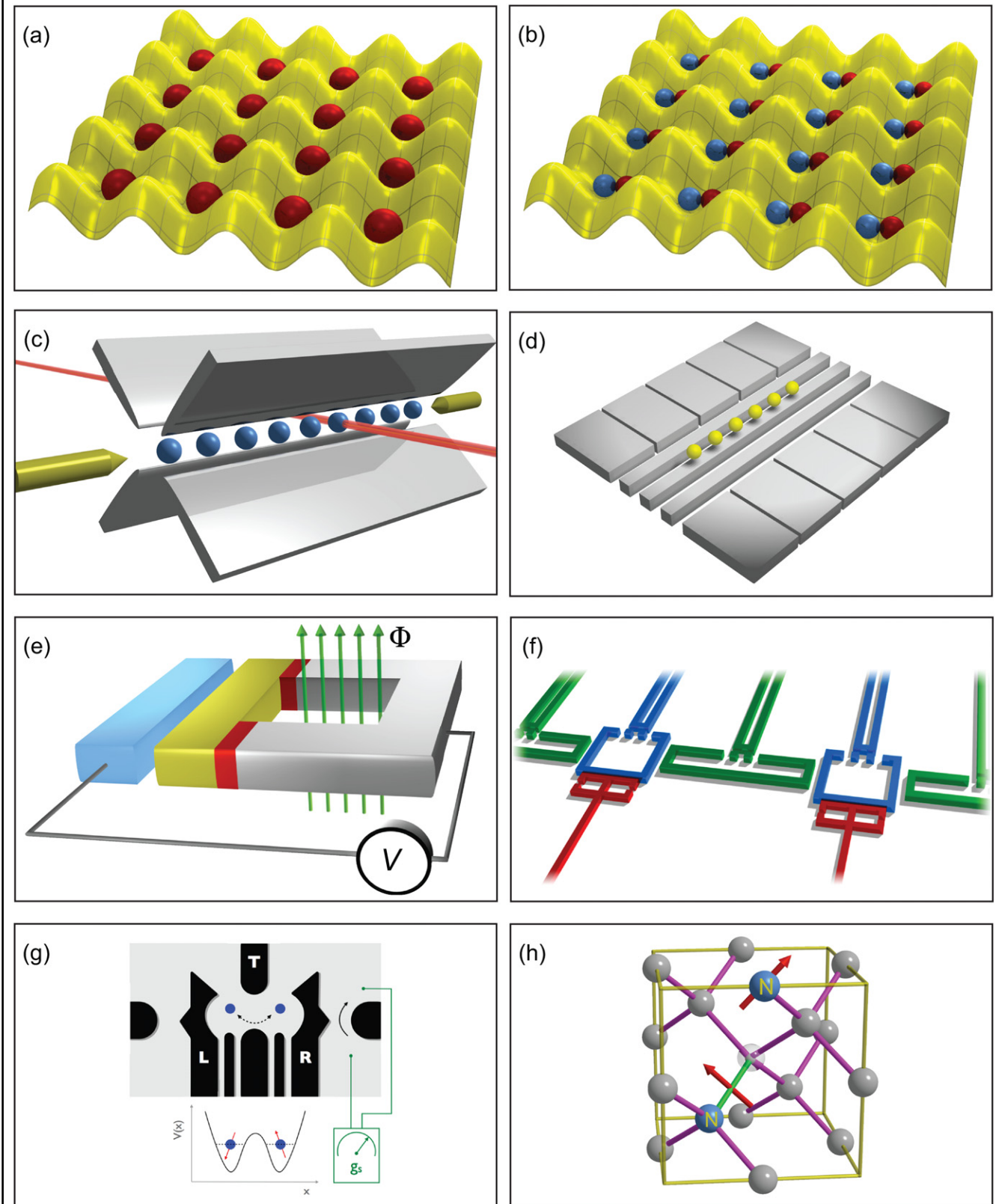
can be controlled by microwaves, voltages, magnetic fields, and currents as well as measured with high accuracy [84] using integrated on-chip instruments. The characteristics of the qubits can be designed and many qubits could be coupled in arrays. Therefore, superconducting qubits are flexible and promise the realization of QC on a chip (see box 2(e) and (f) and table A4).

Superconducting qubits have coherence times that can reach tens of μs (see e.g. [98]), the coupling between qubits can be made strong and can be turned on and off electronically [74, 81]. In addition to direct coupling strategies, superconducting circuits can be coupled via ‘cavities’ [80, 83], which are actually electrical resonators (and the ‘photons’ are actually electron-density oscillations). This setup is promising for the study of circuit cavity quantum electrodynamics (circuit QED) [3, 4, 47, 72, 86].

With superconducting circuits one can now realize simple algorithms [88], and generate entangled states of three qubits [90–92] and arbitrary photon states in a resonator [104]. Other recent advances include the performance of quantum non-demolition measurements [79], the realization of multi-level quantum systems [99, 105], the violation of Bell’s inequality [87, 95], and the coupling of a mechanical resonator to a superconducting qubit [94].

5. Spins in solids

Coherent control and measurement of single spins in solids [9, 58, 106–132] is now possible, and this allows using electron spins in semiconductor quantum dots [116], or electron spins together with nuclear spins in nitrogen-vacancy (NV) color centers in diamond [115] for QC purposes (see box 2(g) and (h)

Box 2. Quantum bits.

Quantum bits can be constructed using a variety of different possible building blocks, of various sizes and properties. As a result, each technology has its unique advantages and challenges.

(a), (b) Hundreds of thousands of neutral atoms can be trapped and cooled at the minima of an optical lattice—the periodic potential created by interfering counter-propagating laser beams. The long-lived internal energy levels of neutral atoms are

Box 2. (Continued.)

used to encode quantum information. Neutral atom qubits can be manipulated with laser radiation and observed via their laser-induced fluorescence. The typical separation between lattice sites is $< 1 \mu\text{m}$, which makes individual addressing challenging. Neutral atoms interact weakly with the environment, which protects them from decoherence. There are several mechanisms for entangling neutral atoms: through state-dependent displacement of the lattice, that results in a highly entangled many-qubit state created in a single operation; through exchange interactions; or via the interaction between two atoms in a double-well potential. Neutral atoms in optical lattices are ideal systems for quantum simulation. (a) illustrates the idea of trapping neutral atoms in periodic optical potentials; one neutral atom qubit is trapped at each lattice site; (b) shows one possible mechanism for creating multi-particle entanglement starting with two atoms in different spin states, trapped in each lattice site.

(c), (d) Ions trapped in electromagnetic fields have been used to encode and manipulate quantum information. The internal energy levels representing the qubit basis states are long-lived and can be easily excited with laser radiation. The typical distance between trapped ions is $5 \mu\text{m}$ or more which facilitates addressing and readout of individual ions. High-efficiency readout is achieved by monitoring the laser-induced fluorescence. Ions in the same potential have a common center-of-mass vibrational mode that can be used as data bus to realize entangling operations. Many-particle entanglement and high-fidelity two-qubit gates have already been demonstrated in experiments. (c) shows a linear trap, while (d) a planar trap. These recently developed micrometer-scale ion traps (d) provide flexibility in manipulating the positions of the ions in two and three dimensions. Nowadays the main focus is on scaling these experiments to large numbers of ions. This can be achieved by moving the ions in the trapping potentials around in complex microstructures, trapping single ions at specific locations in custom-designed lattice geometries created in arrays of microtraps, or by entangling the ions with flying qubits (photons).

(e), (f) Superconducting qubits are micrometer-sized electric circuits based on Josephson junctions. A superconducting qubit (e) can be manipulated using the applied electric voltage V and magnetic flux Φ . Similarly, the qubit can be read out through the small electric or magnetic signal that it produces. Additional circuit elements, called couplers, can be used to provide tunable interactions between the qubits, as shown in (f), allowing the creation of entanglement and the performance of two-qubit gates. Decoherence times have improved from the nanosecond to the microsecond scale over the past decade and are expected to improve further in the future.

(g), (h) Spins in solids arise in a number of distinct realizations. 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, as shown in (g). In the traditional approach, magnetic fields are used to manipulate the qubit, but recent techniques using electric fields and exploiting the exchange and spin-orbit interactions have been developed as well. The qubit is read out by monitoring its response to an applied electric signal. NV centers in diamond, shown in (h), also provide alternative spin qubits. The spin of one electron in the NV chemical bond can be manipulated and read out using magnetic fields and optical-frequency electromagnetic fields. These qubits have long coherence times, on the millisecond timescale. It would be highly desirable to controllably place multiple qubits in an ordered arrangement in the diamond crystal and couple them to each other, such that entanglement and two-qubit gates would be achieved.

and table A5 which attempts to cover, as much as possible in such a short space, several very different systems under the broad umbrella of spins) [5, 106].

Quantum dots are nanoscale structures in which electrons are trapped in all three dimensions. They can be fabricated in several ways, for example, by growth or with electrode gates in a two-dimensional electron gas. The material of choice is usually GaAs. On the other hand, NV centers are point defects in the diamond lattice, consisting of a nearest-neighbor pair made of a nitrogen atom, substituting a carbon atom, and a lattice vacancy. Although in its early stages, quantum computing with electronic and nuclear spins in an array of phosphorus donor atoms embedded in a pure silicon lattice (P:Si) has recently achieved very encouraging results [133–137].

Solid-state qubits such as quantum dots are attractive because, like superconducting circuits, they could be designed to have certain characteristics and assembled in large arrays. Furthermore, they require temperatures of up to a few K (NV centers in diamond could operate even at room temperature).

The manipulation and readout can be done both electrically [118] and optically [117, 119, 123].

While Rabi oscillations have already been observed [113, 121], two-qubit gates have only been demonstrated for NV centers in diamond [109] (although a SWAP gate between logical states has been realized [110]). However, long coherence times [120, 122] have been measured for both quantum dots ($\sim \mu\text{s}$) [126, 127, 128, 129, 132] and NV centers ($> 5 \text{ms}$) [124]. Moreover, for NV centers the entanglement between the electron and nuclear spins has also been shown [124].

Nowadays, nuclear magnetic resonance (NMR) techniques are extensively used in the context of nuclear spins in semiconductors. NMR techniques have been used for the control of nuclear spins in molecules [6, 7, 138–140], which proved very successful for realizing QC with such nuclear spin qubits [6, 7] (see also table A3). A well-known example is the factorization of $N = 15$ using Shor's algorithm [141]. Nuclear spin qubits have long coherence times ($> 1 \text{s}$) and high-fidelity quantum gates have been demonstrated [6]. The coherent

control of up to 12 qubits has also been realized [140]. However, this approach to QC proved difficult to scale up to tens or hundreds of qubits, so NMR techniques are now being applied for the control of nuclear spins in semiconductors. One direction is solid-state NMR [138], but NMR is also merging with electron spin resonance (ESR) methods, so it also becomes relevant for NV centers in diamond and for phosphorus in silicon QC.

6. Comparing natural and artificial atoms

The main characteristics of natural and artificial atoms are displayed in tables 1 and 2. In table 1 T_1 (relaxation time) is the average time that the system takes for its excited state to decay to the ground state; T_2 (decoherence or dephasing time) represents the average time over which the qubit energy-level difference does not vary. We denote by Q_1 (quality factor) the number of one-qubit quantum gates that can be realized within the time T_2 , and by Q_2 (quality factor) the number of two-qubit quantum gates that can be realized within the time T_2 . For implementing QC we are mainly interested in the following aspects: *controllability*, *scalability* and *interfaceability*. The latter will also be discussed in the following section.

The qubit energy-level splittings are comparable for natural and artificial atoms—microwave frequencies (for ions and superconducting circuits) and optical frequencies (for neutral atoms, ions and some semiconductor quantum dots). Box 1 displays schematically the potential energies and discrete energy levels for natural and artificial atoms in the absence ($E = 0$) and in the presence ($E \neq 0$) of an external field. While natural atoms are usually driven using optical or microwave radiation, artificial atoms like superconducting circuits can be driven by currents and voltages, magnetic fields, as well as microwave photons. Optically driven artificial atoms, such as some semiconducting quantum dots, have also been demonstrated. Artificial atoms can be engineered to have a large dipole moment or particular transition frequencies. Depending on the intended application this tunability may prove quite useful.

In natural atoms, motional states can also be exploited for encoding the qubits or as data bus. The motional frequency can be controlled, but the cooling of these modes is usually necessary if they are to be used for QC purposes. For artificial atoms, resonators can play a similar role to the motional modes. The frequency of these resonators can also be controlled, and they can be cooled much like atoms. For instance, the temperature of superconducting circuits can be decreased using cooling techniques inspired from atomic physics, such as sideband or Sisyphus cooling [142, 143]. Natural atoms have many energy levels which can be used to encode information. Levels that are well protected against decoherence (i.e. magnetic-field-independent hyperfine transitions [144]) could be used for memory qubits, while fast transitions could be used for implementing two-qubit gates. Furthermore, realizing qubits in natural atoms is straightforward.

Unlike natural atoms of the same species, which are indistinguishable, no two artificial atoms will be perfectly alike. With the latest advances in microfabrication, artificial

atoms can be made with increasing accuracy and uniformity. However, this is an extra challenge. While natural atoms are readily available and one only needs to trap them by means of optical or electrical fields and then cool them to low temperatures, artificial atoms have to be carefully designed and fabricated. Furthermore, atom and ion trapping technologies have been in use for quite a while, but for artificial atoms the techniques are more recent.

Artificial atoms can be produced in large numbers and ‘wired’ together on a chip. Therefore, extending current experiments to large numbers of artificial atoms should, in principle, not be a problem. Neutral atoms can be loaded by thousands or millions in optical lattices; however, individual addressing has not yet been fully demonstrated [29]. Meanwhile, in the case of ions, although several proposals are available, scaling to large numbers is a challenge. Natural atoms are not wired so they can form almost any 2D or 3D configuration; however, for artificial atoms the wiring itself may impose some geometric limitations. Neutral atom and trapped ion qubits can also be moved around easily. This flexibility may prove advantageous for certain applications.

Both natural and artificial atoms can be coupled with photons via cavity QED [3, 4, 86], which could provide a means of realizing large-scale QC and long-distance quantum communication (see also [145]). The physics of cavity QED is the same regardless of the nature of the atom or cavity, but, for artificial atoms (e.g. circuit QED) the coupling strength is several orders of magnitude larger than for natural atoms [3, 4, 86]. Several exciting experiments demonstrating the coupling between cavities and natural or artificial atoms have been performed (see, for instance, [80, 83, 146–148] and the review in [103]).

As for the operating conditions, natural atoms can be coherently manipulated only in an ultrahigh vacuum at very low temperatures (nK– μ K for neutral atoms and mK for ions). Artificial atoms are also operated at low temperatures (mK in the case of superconducting circuits or a few K for semiconductor quantum dots), but there are some candidates for room-temperature qubits, including very long coherence times for NV centers in diamond (note that their T_1 is temperature dependent).

7. Photons

Photons can also make good qubits and they can carry quantum information over long distances hardly being affected by noise or decoherence. The qubit states can be encoded, for example, in the polarization of a single photon, and one-qubit gates can be easily realized with optical elements [11, 149]. Unfortunately optical QC has a serious drawback: the difficulty in implementing two-qubit gates. Realizing the nonlinearity required for entangling two qubits is challenging, so alternatives such as the teleportation of nondeterministic quantum gates have been investigated [149]. While this approach is still impractical due to the large amount of required resources, another solution may be found in measurement-based QC.

Table 1. Comparison between natural and artificial atoms.

	Natural atoms		Artificial atoms	
	Neutral atoms	Trapped ions	Supercond. circuits	Spins in solids
Energy gap	GHz (hyperfine), 10^{14} Hz (optical)	GHz (hyperfine), 10^{14} Hz (optical)	1–10 GHz	GHz, 10^{13} Hz
Photon	Optical, MW	Optical, MW	MW	Optical, MW, infrared
Dimension	$\sim 2 \text{ \AA}$	$\sim 2 \text{ \AA}$	$\sim \mu\text{m}$	$\sim \text{nm}$
Distance between qubits	$< 1 \mu\text{m}$	$\sim 5 \mu\text{m}$	$\sim \mu\text{m}$	$\sim 10 \text{ nm}^{\text{a}}$, $\sim 100 \text{ nm}^{\text{b}}$
Operating temperature	nK– μK	μK –mK	$\sim \text{mK}$	mK–300 K
Qubit interactions	Collisions, exchange	Coulomb	Capacitive, inductive	Coulomb, exchange, dipolar
Cooling	Doppler, Sisyphus, evaporative	Doppler, sideband	Cryogenic	Cryogenic
Cavity	Optical, MW	Optical, vib. modes	Transmission line, LC circuit	Optical, MW

^a Distance between qubits for NV centers.

^b Typical distances between quantum dots.

Table 2. Comparison between natural and artificial atoms in view of implementing QC. Hereafter, MW stands for microwaves and SC for superconducting.

	Natural atoms		Artificial atoms	
	Neutral atoms	Trapped ions	Supercond. circuits	Spins in solids
# entangled qubits	2 ^a	14	3 (4 ^b)	1 (3 ^c)
One-qubit gates fidelity	99%	99%	99%	$> 73\%$ ($> 99\%$ ^c)
Two-qubit gates fidelity	$> 64\%$	99.3%	$> 90\%$	90% ^c
Entangled states	Bell	Bell, GHZ, W, cat	Bell, GHZ ^d W, cat	GHZ ^c
Measurement efficiency	99.9%	99.9%	$> 95\%$	99%
T_1	$\sim \text{s}$	$\sim 100 \text{ ms}^{\text{e}}$ $> 20 \text{ ms}^{\text{f}}$	$10 \mu\text{s}$	$\sim 1 \text{ s}^{\text{g}}$
T_2	$\sim 40 \text{ ms}$	$1000 \text{ s}^{\text{h}}$	$20 \mu\text{s}$	$200 \mu\text{s}^{\text{g}}$
Q_1	$\sim 10^4$	$\sim 10^{13}$	$\sim 10^5$	$\sim 10^3$ – 10^4 (10^6 ^c)
Q_2	$\sim 4 \times 10^4$	2×10^2 – 2×10^3 $\sim 2 \times 10^4$	> 100	tbd
Interfaceable with	Photons, SC circuits	Photons, SC circuits	Photons, atoms, ions	Photons

^a Large entangled states can also be realized with collisional gates.

^b Entanglement of the ground state of four qubits.

^c NV centers in diamond.

^d Only generated for one and two resonators and not for many qubits.

^e T_1 for the vibrational modes.

^f T_1 for the internal hyperfine states.

^g Of the order of ms for NV centers at room temperature and of the order of minutes at 1 K; of the order of seconds for P : Si;

^h In optical clocks $T_1, T_2 > 10 \text{ min}$ has been observed.

Table 3. Interfacing different types of qubits for future scalability or realizing long-range quantum communication. The asterisk denotes the cases that have been experimentally realized and the dash means that, to the best of our knowledge, no proposal exists yet.

	Atoms	Ions	Cavity	Spins	SC
Atoms		✓	✓*	—	✓*
Ions	✓		✓*	—	✓
Cavity	✓*	✓*		✓	✓*
Spins	—	—	✓		✓
SC	✓*	✓	✓*	✓	

For the moment photons may not be practical as memory or computation qubits, but they are certainly the best ‘flying qubits’. Recent advances in quantum communication and, in particular, quantum key distribution are reviewed in [10].

8. Hybrids

Exploiting the advantages of both natural and artificial atoms in hybrid systems provides exciting prospects for realizing QC. For instance, ions [150, 151] and atoms [152, 153] interfaced with superconducting circuits are now being investigated. As recent results point out neutral atoms and ions could also be interfaced with each other [154, 155]. While cavity QED with atoms and ions has been studied for some time now [86, 145], solid-state cavity QED is more recent [80, 83, 86, 148]. For natural atoms strong coupling has been demonstrated [146, 147]. As mentioned before, in circuit QED the coupling strength is many orders of magnitude larger than in cavity QED, which is very promising for the study of quantum optics on a chip. As shown in table 3, all systems discussed in the previous sections can be coupled with other systems. It is interesting to note that superconducting circuits can be coupled with different types of natural atoms, spins in solids [156–158] and with photons.

Natural atoms, with their long decoherence times, are envisaged by many as quantum memories [159], while the tunable artificial atoms may be used for the ‘quantum processing unit’. Both natural and artificial atoms may be coupled with photons via a cavity. Note that a necessary requirement is for the coupling timescale to be shorter than the decoherence time. Such cavities could be used as input/output interfaces and for long-distance communication. Perhaps the first functional quantum computer will be a complex hybrid system made of natural atoms, artificial atoms, and photons. Such a hybrid device is represented schematically in figure 1. Several types of hybrids are discussed in [160].

9. Prospects

In both natural and artificial atoms, almost all the basic requirements for realizing QC [161] have been demonstrated (i.e. (i) a scalable system with well-characterized qubits; (ii) initialization of the qubits; (iii) reasonably long decoherence times; (iv) a universal set of quantum gates; (v) measurement of the qubits). Tables 1–6 and figure 2 provide a brief snapshot of

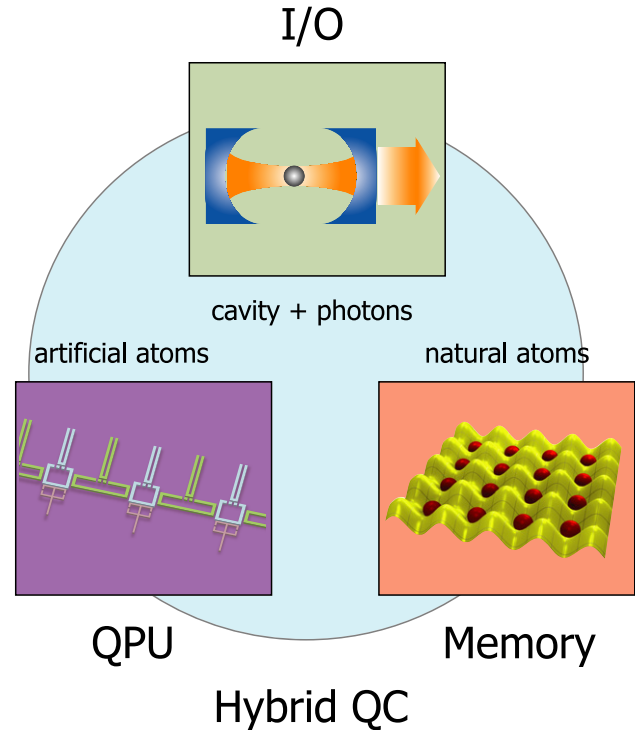


Figure 1. Schematic representation of a hybrid device consisting of natural atoms as quantum memory, artificial atoms as the ‘quantum processing unit’ (QPU), and an input/output (I/O) photonic interface.

Table 4. Coherence times of superconducting qubits.

Year	T1	T2 (echo)	Qubit	Ref.
1999	1 ns	—	Charge	[65]
2002	580 ns	2 ns	Charge	[66]
2002	100 ns	100 ns	Phase	[67]
2002	1.8 μ s	500 ns	Hybrid (charge/phase)	[68]
2003	0.9 μ s	30 ns	Flux	[69]
2006	1.9 μ s	3.5 μ s	Flux	[77]
2008	1.87 μ s	2.22 μ s	Hybrid (charge/phase)	[85]
2009	350 ns	—	Flux	[89]
2010	1.6 μ s	1.3 μ s	Hybrid (phase/flux)	[96]
2011	12 μ s	23 μ s	Flux	[98]
2011	0.2 ms	—	Charge	[101]

the current progress and experimental status for several types of qubits.

The current challenges are to attain increased controllability (and minimize decoherence) and scale the existing systems to tens and hundreds of qubits and many-gate operations. At this stage, new milestones, such as the creation of many-particle entangled states, the implementation of small quantum algorithms, and other applications (e.g. quantum simulation), and the realization of quantum communication by interfacing the qubits with photons, are being targeted.

‘Quantum supercomputers’ for factorizing large numbers are still a distant goal. The first generation of practical quantum computers may be either specialized devices for scientific applications like quantum simulations [162], or integrated in complex quantum networks [145]. As the very positive results

Table 5. Progress in the implementation of superconducting qubits quantum gates.

Year	Operation	Qubits	Mechanism	Ref.
2003	CNOT gate	2	Direct coupling; gate relies on zz component	[71]
2003	Entangled energy levels	2	Direct xy coupling	[70]
2005	iSWAP; Entanglement	2	Direct xy coupling	[73]
2006	iSWAP; Entanglement	2	Direct xy coupling	[76]
2006	Entangled energy levels	4	Direct coupling	[75]
2006–7	Controllable coupling	2	Coupling mediated by additional circuit element	[74, 78]
2007	CNOT gate	2	Direct coupling; gate relies on zz component	[82]
2007	iSWAP	2	xy coupling to cavity; gate mediated by cavity	[83]
2007	iSWAP	2	xy coupling mediated by cavity	[80]
2007	iSWAP	2	Coupling mediated by additional circuit element; gate relies on xy coupling	[81]
2009	CPhase	2	zz coupling mediated by auxiliary energy levels	[88]
2010	Entanglement	3	xy coupling	[90]
2010	Entanglement	3	zz coupling mediated by auxiliary energy levels	[91]
2011	3-qubit gate	3	Coupling mediated by auxiliary energy levels	[97]

Table 6. Progress in the number of qubits and fidelities for different operations on trapped ions. CZ stands for the Cirac–Zoller scheme [163], and MS for the Mølmer–Sørensen scheme [164].

Year	Operation	Mechanism	Qubits	Fidelity	Ref.
1998	Entanglement	CZ	2	70%	[40]
2000	Entanglement	MS	2	83%	[42]
			4	57%	
2003	CNOT gate	CZ	2	71.3%	[43]
2003	Entanglement	Geometric	2	97%	[45]
2005	Entanglement	CZ	4	>76%	[52]
			5	>60%	
			6	>50%	
2005	Entanglement	CZ	4	85%	[51]
			5	76%	
			6	79%	
			7	76%	
			8	72%	
2006	CNOT gate	CZ	2	92.6%	[53]
2008	Entanglement	MS	2	99.3%	[56]
2009	Toffoli gate	CZ	3	74%	[60]
2010	Entanglement	MS	10	62.9%	[64]
			12	39.6%	
			14	46.3%	

summarized above point out, the first-generation quantum computers may be available in the near future. Furthermore, they may come as hybrids consisting of natural atoms, artificial atoms, and photons.

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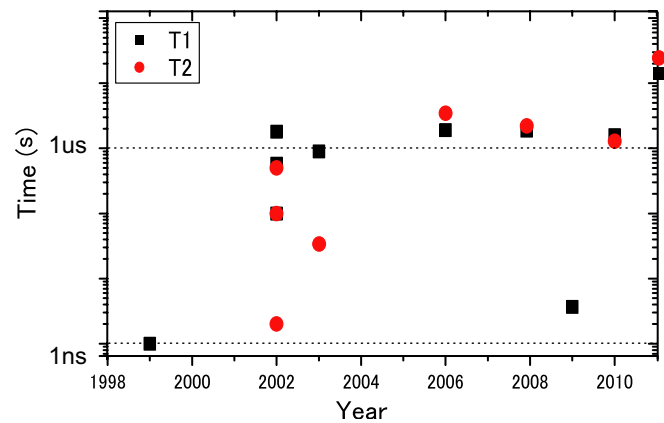


Figure 2. An example of the progress that has been achieved for superconducting circuits in the last decade. The decoherence time kept increasing, and the current trend promises decoherence times of the order of ms in the next couple of years. Visibility also increased and now it is larger than 95%. The black squares show T_1 and the red dots T_2 .

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Appendix. Tables summarizing the main characteristics of different systems in view of realizing quantum computation

In the following tables, T_1 (relaxation time) is defined as the average time that the system takes for its excited state to decay to the ground state; T_2 (decoherence time) represents the average time over which the qubit energy-level difference does not vary; Q_1 (quality factor) represents the number of one-qubit quantum gates that can be realized within the time T_2 ; Q_2 (quality factor) represents the number of two-qubit quantum gates that can be realized within the time T_2 . The following abbreviation is used: tbd for ‘to be demonstrated’

Table A1. Neutral atoms.

<i>Neutral atoms</i>	
Qubits	Internal states (ground hyperfine states); motional states (trapping potential eigenstates)
Scalability	Demonstrated in optical lattices; possible in arrays of cavities, atom chips
Initialization	Both internal (optical pumping) and motional (laser cooling) states
Long coherence time	Several seconds [15, 19, 30]
Universal quantum gates	One-, two-qubit gates (several proposals)
Measurement	Fluorescence: ‘quantum jump’ technique
<i>Fabrication</i>	
Material	Trapped neutral atoms: Rb, Li, K, Cs, etc
Well-controlled fabrication	Yes
Flexible geometry	Yes (especially in optical lattices)
Distance between qubits	A few hundred nm to a few μm [1]
<i>Operation</i>	
Qubits demonstrated	$> 10^6$ (stored), 2 (entangled)
Superposition/Entangled states	Yes/yes
One-qubit gates (Fidelity)	Yes (99.98%)
Two-qubit gates (Fidelity)	Yes (SWAP $> 64\%$ [20]); CNOT (73% [33])
Operation temperature	From nK to μK
<i>Readout</i>	
Readout (Fidelity)	Laser-induced fluorescence (99.9%)
Single-qubit readout possible	Yes
<i>Manipulation</i>	
Controls	Optical fields, microwave
Types of operations	One-, two-qubit gates, entanglement
Individual addressing	tbd [24, 29, 31, 32, 35]
<i>Decoherence</i>	
Decoherence sources	Photon scattering, heating, stray fields, laser fluctuations
T_1	$\sim\text{s}$
T_2	$\sim 40\text{ ms}$
Q_1	$\sim 10^4$
Q_2	$\sim 40\,000$

Table A2. Trapped ions.

<i>Trapped ions</i>	
Qubits	Internal states (hyperfine or Zeeman sublevels, optical); motional states (collective oscillations)
Scalability	Ion shuttling, arrays, photon interconnections, long strings
Initialization	Both internal (optical pumping) and motional (laser cooling) states
Long coherence time	Internal: hyperfine $> 20\text{ s}$, optical $> 1\text{ s}$; motional: $\sim 100\text{ ms}$
Universal quantum gates	One-, two-, three-qubit gates
Measurement	Fluorescence: ‘quantum jump’ technique
<i>Fabrication</i>	
Material	Atomic ions: Ca^+ , Be^+ , Ba^+ , Mg^+ , etc
Well-controlled fabrication	Yes
Flexible geometry	Yes
Distance between qubits	A few μm to tens of μm
<i>Operation</i>	
Qubits demonstrated	$10\text{--}10^3$ (stored), 14 (entangled) [64]
Superposition/entangled states	Yes/yes (2–14 ions, fidelities 99.3%–46%) [64]
One-qubit gates (fidelity)	Yes (99%)
Two-qubit gates (fidelity)	Yes (CNOT $> 99.3\%$ [56]; Toffoli 71.3% [60]; gate time 1.5 ms)
Operation temperature	From μK to mK
<i>Readout</i>	
Readout (fidelity)	Laser-induced fluorescence (99.9%)
Single-qubit readout possible	Yes
<i>Manipulation</i>	
Controls	Optical, microwave, electric/magnetic fields
Types of operations	One-, two-, three-qubit gates, entanglement
Individual addressing	Yes
<i>Decoherence</i>	
Decoherence sources	Heating, spontaneous emission, laser, magnetic field fluctuations
T_1	a few minutes (hyperfine), 1 s (optical), 100 ms (motional)
T_2	15 s
Q_1	$\sim 10^{13}$ (single-qubit gate 50 ps) [63]
Q_2	$\sim 20\,000$ (MS gate 50 μs) [56]; ~ 200 (CZ gate 500 μs) [53]

Table A3. Nuclear spins manipulated by NMR.

<i>NMR</i>	
Qubits	Nuclear spin
Scalability	Not available in liquid-state NMR; possible for solid-state NMR
Initialization	Demonstrated
Long coherence time	> 1 s
Universal quantum gates	One-, two-, three-qubit gates
Measurement	Single-qubit measurement not available
<i>Fabrication</i>	
Material	Organic molecules (alanine, chloroform, cytosine)
Well-controlled fabrication	Yes
Flexible geometry	No
Distance between qubits	~Å
<i>Operation</i>	
Qubits demonstrated	7, 12 (entangled) liquid-state [140]; > 100 (correlated) solid state
Superposition/entangled states	Yes/yes
One-qubit gates (fidelity)	Yes (>98%)
Two-qubit gates (fidelity)	Yes (>98% CNOT and SWAP)
Operation temperature	Room temperature
<i>Readout</i>	
Readout (fidelity)	Voltage in neighboring coil induced by precessing spins, 99.9%
Single-qubit readout possible	No
<i>Manipulation</i>	
Controls	RF pulses
Types of operations	One-, two-, three-qubit gates
Individual addressing	No
<i>Decoherence</i>	
Decoherence sources	Coupling errors
T_1	> 1 s (liquid state); > 1 min (solid state)
T_2	~1 s (liquid state); > 1 s (solid state)
Q_1	
Q_2	100 (gate time 10 ms)

Table A4. Superconducting circuits.

<i>Superconducting circuits</i>	
Qubits	Flux, phase states, charge; also hybrids
Scalability	High potential for scalability
Initialization	Demonstrated for all types of qubits
Long coherence time	~ 10 μ s
Universal quantum gates	One-, two-qubit gates
Measurement	Individual measurement possible
<i>Fabrication</i>	
Material	Josephson junctions (Al–Al _x O _y –Al, Nb–Al _x O _y –Nb)
Well-controlled fabrication	Yes
Flexible geometry	Yes
Distance between qubits	~ μ m
<i>Operation</i>	
Qubits demonstrated	128 (fabricated) [93], 3 (entangled)
Superposition/entangled states	Yes/yes
One-qubit gates (fidelity)	Yes (99%)
Two-qubit gates (fidelity)	Yes (>90%) [88]
Operation temperature	mK
<i>Readout</i>	
Readout (fidelity)	SET, SQUID (>95%) [84], cavity frequency shift [72]
Single-qubit readout possible	Yes
<i>Manipulation</i>	
Controls	Microwave pulses, voltages, currents
Types of operations	One-, two-, three-qubit gates, entanglement
Individual addressing	Yes
<i>Decoherence</i>	
Decoherence sources	Electric and magnetic noise, 1/f noise
T_1	0.2 ms [101]
T_2	23 μ s [98]
Q_1	~10 ⁵
Q_2	> 100 (gate time 10–50 ns) [88]

Table A5. Spins in solids. Here, QDs stand for quantum dots, NV centers for nitrogen-vacancy centers in diamond and P : Si for phosphorous on silicon.

<i>Spins in solids</i>	
Qubits	Electron spin; electron and nuclear spins in NV centers, P : Si
Scalability	High potential for scalability
Initialization	Demonstrated
Long coherence time	> 1 s (QDs); ~s (NV centers), ~100 s (P : Si)
Universal quantum gates	One-qubit gates
Measurement	Electrical, optical
<i>Fabrication</i>	
Material	GaAs, InGaAs (QDs), NV centers, P : Si
Well-controlled fabrication	Yes
Flexible geometry	Yes
Distance between qubits	100–300 nm (QDs); ~10 nm (NV centers)
<i>Operation</i>	
Qubits demonstrated	1 (QDs), 3 (NV centers) [124]
Superposition	Yes
One-qubit gates (fidelity)	Yes (>73% QDs [113]; >99% NV centers [130])
Two-qubit gates (fidelity)	Yes (90% NV centers [109])
Operation temperature	From mK to a few K (QDs); room temperature (NV centers)
<i>Readout</i>	
Readout (Fidelity)	Electrical, optical (90–92%)
Single-qubit readout possible	Yes
<i>Manipulation</i>	
Controls	RF, optical pulses, electrical
Types of operations	One-qubit gates (>73% gate time 25 ns)
Individual addressing	Yes
<i>Decoherence</i>	
Decoherence sources	Co-tunneling, charge noise, coupling with nuclear spins
T_1	> 1 s (QDs) [120]; >5 ms ^a (NV centers) [124]; 6 s [133] (P : Si); 100 s [134] (P : Si)
T_2	~270 μ s [129, 128]; ~1.8 ms (NV centers) [125]; ~60 ms [107] (P : Si); 2 s [9] (P : Si)
Q_1	~10 ³ (gate time 180 ps); ~10 ⁴ (gate time 30 ps) [121]; >10 ⁶ (gate time ~1 ns)
Q_2	tbd

^a Room temperature.

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Due to space limitations we list a small subset of recent, relevant papers, mostly experimental results. The very few theory papers cited here introduce parameters used in the experimental papers cited, and also in the tables (e.g. as in table 6). For more references on the theoretical aspects, please refer to the various more specialized reviews listed below.

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