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NTT Press Releases

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A new method toward the realization of a million-bit-scale quantum computer

- Entangling all the atoms in an optical lattice for computational resource -

Nippon Telegraph and Telephone Corp. (NTT; Head Office: Chiyoda-ku, Tokyo; President: Hiroo Unoura) proposed a method for generating a large-scale entangled quantum state(*1) of ultracold atoms in an optical lattice(*2) with high fidelity and short operation time, which becomes a resource for quantum computers(*3). This result solves important problems toward the realization of a quantum computer, such as scalability of quantum bits and decreasing the errors. This result paves the way for realizing a million-bit-scale quantum computing.

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1. Background

The biggest challenges for realizing a quantum computer (Fig. 1) are obtaining a scalability of quantum bits and decreasing the errors. An optical lattice recently gets attention as a good candidate for solving these problems. In an optical lattice (Fig. 2), single atom can be periodically confined in each site of the lattice with a distance of about light wavelength (< 1 μm). Compared to the other physical systems, an optical lattice is expected to be a great technology that can store many atoms in a very small volume and in a highly ordered manner, where atoms can serve as uniform and ideal quantum bits. An optical lattice clock(*4) (Fig. 3) is a promising application of this technology and has already been experimentally demonstrated. If one can make a special large-scale entangled quantum state (Fig. 4) among huge number of atoms, then one can realize measurement-based quantum computation by performing individual atom measurements on it, which are more simple operations compared to quantum gates (Fig. 5). An optical lattice can compactly array many atoms, however, we have not yet established any method that can generate a large-scale entangled quantum state with high fidelity and short operation time, which are necessary for the realization of a quantum computer.

2. Achievements

NTT basic research laboratories and NTT secure platform laboratories have collaborated to exploit their advanced techniques on ultracold atoms and quantum information processing to this achievement. They, for the first time, successfully proposed a method for generating a large-scale entangled quantum state of atoms confined in optical lattice with high fidelity (>99%) and short operation time (~1ms), which can be used as a computational resource for quantum computing. The existing methods have tradeoffs such that high-fidelity gate operations work slowly or fast gate operations offer low fidelity. Moreover, the existing methods have a problem that multi-bit operation makes a crosstalk and causes a serious error. In this research, NTT proposes a new entanglement generation method with high fidelity, short operation time and scalability, which solves the above tradeoffs by ingeniously controlling several laser lights for designing the optical lattice. This result opens up a possibility of the realization of quantum computer with a million scale quantum bits.

3. Technical features

(1) Atoms in an optical lattice for quantum bits

An optical lattice is an artificial crystal made by lasers and an ideal crystal without defects and impurities. This crystal has a periodic structure with a distance of about light wavelength (< 1 μm) and can stably confine an atom in each lattice site. With the present technology, one can confine about a million atoms within a 3-dimensional space with 100 μm on a side. We can use the huge number of atoms as homogeneous and ideal quantum bits.

(2) Entanglement generation method with high fidelity, short operation time, and scalability

In order to decrease the errors of quantum bits, they should not interact with each other. However, when one tries to make entanglement between quantum bits, they have to interact with each other and this results in producing unwanted errors (Fig. 6). In this research, NTT proposes a method to utilize only one physical state for mediating quantum bits and actively use it as an ancillary state, then we succeed to make high-fidelity quantum entangling gates (Fig. 7). We propose a “phase-tuning method” (Fig. 8) for solving the tradeoff between fidelity and operation time, a “pair-wise control method” (Fig. 9) for generating entanglement in parallel without producing a crosstalk, and an “error removal method” (Fig. 10) for obtaining a better error-tolerance by converting errors to losses. The great advantage is that this method can be simply implemented by combining the currently established technologies such as controlling the wavelength and strength of laser (microwave) lights. The present limit of the scale (about a million atoms) only depends on the atom trap technology. If much greater number of atoms can be trapped in future, this method can be applied in the same way.

(3) Performance verification by exact numerical simulations

We verified the performance of this method by ab-initio physical modeling and exact numerical simulations (*5). Ultracold atoms in an optical lattice are considered to be a clean and ideal physical system, which makes a theoretical evaluation highly realistic. Therefore this method will be faithfully realized in an experiment.

4. Future plans

We plan to study the detailed conditions for experimentally demonstrating the generation of large-scale entangled quantum state based on the present method. In parallel, we plan to develop an essential experimental technique for measuring the quantum state of individual atoms. Moreover, we try to generate the entangled quantum state in a two-dimensional optical lattice, where the individual atom measurement is easier to perform in contrast to the three dimensional case, and try to demonstrate the measurement-based quantum computation in a scale of 10,000 quantum bits within five years. Our goal is to realize a large-scale quantum computation using one million quantum bits in a three-dimensional optical lattice.

Glossary

(*1) Entangled quantum state

Quantum mechanics allows a specific state such that multiple quantum bits have an unusual correlation beyond classical physics. For example, if two quantum bits are spatially separated but entangled with each other, the physical operation on one quantum bit influences the other. We can utilize this correlation for quantum computing and quantum teleportation.

(*2) Optical lattice

An artificial lattice structure produced by the interference of laser lights. The lattice distance of optical lattice is of the order of light wavelength. We can confine atoms on the lattice sites one by one and utilize them as quantum bits, which provides a great advantage for collecting many atoms in a small volume.

(*3) Quantum computer

A computer to perform various information processing using quantum bits. Beyond the modern computers, a quantum computer can show the extraordinary performance in prime factorization and database searching by utilizing quantum mechanical superposition and quantum entanglement during computational operations.

(*4) Optical lattice clock

An atom clock which is developed in recent years based on optical lattices. Accuracy and stability of atom clock have been dramatically improved by using an ensemble of many atoms tightly confined in an optical lattice.

(*5) Ab initio modeling and exact numerical simulations

We model the atoms confined in an optical lattice in an ab initio manner without any approximations and exactly calculate their quantum mechanical states and dynamics. This accurate analysis is possible only when the number of atoms is sufficiently small. We can investigate the scalability by examining how the fidelity changes as the number of atoms gradually increases.

Attachment·Reference

- Fig. 1: Quantum computer
- Fig. 2: Optical lattice and cold atoms
- Fig. 3: Applications of optical lattices ~from optical lattice clock to quantum computer~
- Fig. 4: Quantum entanglement
- Fig. 5: Measurement based quantum computation
- Fig. 6: Entanglement between atoms
- Fig. 7: New schemes for entanglement generation
- Fig. 8: Phase tuning scheme (for simultaneous achievement of high-fidelity and short operation time)
- Fig. 9: Pairwise control scheme (for scalability)
- Fig.10: Error removal scheme (for practical progress)

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