Cluster State Quantum Computation with Molecular Rotational States

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Abstract. We propose an architecture for a cluster state quantum computation using rotational-state qubits of nonpolar ionic molecules trapped in a two-dimensional array of ion traps. It is shown that the rotational-state qubits are much more immune to decoherence than the electronic-state qubits of atomic ions, so the prepared cluster state can preserve its quantum coherence very long time.

Keywords: quantum computation, cluster state, molecule, rotational state

There are two approaches to the quantum computing: one that *molds* quantum state while the other *sculptures* it. Molding of quantum states is the original scheme for quantum computers that are based on quantum circuits. On the other hand, Raussendorf and Briegel introduced a giant maximally entangled state of many qubits called a cluster state [1] and proposed cluster state quantum computation with Browne [2]. After preparing a cluster state, sculpturing is performed by measuring each qubit feedforwardly based on the previous measurement results.

One obstacle in realizing the cluster state quantum computer is that it needs much more qubits to be prepared than the quantum-circuit-based approaches, because a cluster state requires a two-dimensional array of qubits. Another obstacle is that decoherence should well be protected during sculpturing processes that might take long time. Although several proposals have been made to physically implement the cluster state quantum computer [3], it seems difficult to overcome the above obstacles.

Here we propose a new scheme to realize a cluster state quantum computer. As qubits, we adopt rotational states of nonpolar molecular ions trapped in a two-dimensional array of ion traps. It has been reported that, in an ion trap, rotational-state qubits of nonpolar molecular ions are much more immune to decoherence than conventional electronic-state qubits of atomic ions [4]. Furthermore, the state-of-the-art ion-trap technology can transport the ions in an array of ion traps [5], so every pair of neighboring ions can be approached closely and can undergo a two-qubit entangling gate. With this two-dimensional array of ion traps, molecular rotational-state qubits can constitute large-scale cluster state.

In an ion-trap quantum computer, the major source of decoherence is a fluctuating magnetic field [6] which causes Zeeman shift through magnetic dipole moments that qubits have. The single-qubit coherence time of an atomic ion has been achieved to be about 20 s [7]. However, 20 s is not sufficient for a large-scale quantum computer because if the coherence time of a single qubit is τ, then that of N qubits is approximately τ/N [8]. Yun et al. [4] revealed that the magnetic dipole moment of the rotational-state qubit of NS_2^+ molecule is five order smaller than that of conventional electronic-state qubits of atomic ions such as Be^+ or Mg^+. Thus the rotational-state qubits are expected to have several order longer coherence time than that of atomic electronic-state qubit.

The first step in operating a quantum computer is the state preparation of qubits, which should include translational, vibrational, and rotational cooling of molecular ions. The translational cooling of molecular ions can be achieved by the sympathetic cooling method that relies on co-trapped atomic ions that can be easily cooled down by a laser [9]. For rovibrational cooling, a method that exploits the motional state shared with atomic cooling-pair ions was proposed [10]. This method is expected to make nonpolar molecular ions reach the rotational ground state, i.e. $|\downarrow\rangle$, with high fidelity of more than 99.9% in near future [10].

Rotationally stationary states of a linear molecule are angular momentum eigenstates $|J,M\rangle$. We choose qubit levels such that $|\downarrow\rangle \equiv |0,0\rangle$ and $|\uparrow\rangle \equiv |2,0\rangle$. Nonpolar molecules allow rotational two-photon Raman transitions with $\Delta J = \pm 2$ due to anisotropy in their polarizability. With this Raman transition, a single-qubit gate can be achieved by two-color laser field that causes the resonant Raman-Rabi oscillation between qubit levels. To achieve two-qubit entangling gate, conventional schemes such as Cirac-Zoller gate or Sørensen-Mølmer gate developed in an ion trap can also be applied to the rotational-state qubits of molecular ions. Because these gates exploit motional states that two ions share, they work regardless of whether the qubits reside on electronic states or rotational states.

Cluster state can be made by the following way. After state preparation to $|\downarrow\rangle$, each qubit is applied to Hadamard gate and becomes superposition state $\frac{1}{\sqrt{2}}\left(|\downarrow\rangle + |\uparrow\rangle\right)$. By transporting ions, one can cotrap two neighboring ions in a single trap potential. Controlled-Z gate applies to the pair. When all possible neighboring pairs are done, the cluster gate is prepared.

Cluster state quantum computing is measurement-based quantum information processing. To measure rotational-state qubit, we use state-transfer technique. In an ion trap with two ions co-trapped, an internal state of one ion can be transferred to that of the other ion [11]. With this technique, the rotational-state qubit of a molecular ion can be readout by instead measuring the electronic-state qubit of an atomic ion that has a good cycling transition [4].

In conclusion, we have proposed a new architecture for a cluster state quantum computation using rotational-state qubits of nonpolar ionic molecules trapped in a two-dimensional array of ion traps. It was shown that the rotational-state qubits are very immune to decoherence, so the prepared cluster state can preserve its quantum coherence very long time. A complete method set necessary for building a cluster state quantum computer suitable for the rotational-state qubits was also provided.

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