Quantum gates with atomic ensembles on an atom chip

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We propose a scheme for implementing quantum computation with atomic ensembles on an atom chip, where a single qubit is carried by an atomic ensemble instead of a single atom. Two electronic ground states of the atoms are involved, one state with one or no atom is used to represent the qubit and the other state is used to hold the residual atoms. One and two-qubit gates are implemented by internal state transition with laser pulse sequences in the presence of the exciting blockade mechanism. A scalable quantum computer can be realized by one-dimensional or two-dimensional atomic lattices on an atom chip.

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Since the discovery of quantum algorithms can provide exponential gains for solving some problems, such as the searching and factoring problems [1,2], numerous proposals have been advanced for implementing quantum computation (QC) [3–8]. The neutral atom is one of the promising candidates for implementing QC, for its weak interaction with the environment, long coherence time, and mature manipulating techniques [9–12].

Especially the development of the atom chip opens a door for precise control and manipulation of neutral atoms [13,14]. What is more, the atom chip also combines a lot of other important features for implementing QC [15–19]: it is scalable; it allows individual addressing; and it can be integrated with other devices, such as cavity, detector, and optical devices. However, there is still no experimental demonstration of implementing QC on an atom chip, because all of the proposals, either the collision gate or the cavity assisted gate, request manipulating a single atom on an atom chip. On the other hand, both the collision phases and the coupling of a single photon with a single atom are very hard to control.

In this Brief Report, we propose a scheme for implementing quantum gates with atomic ensembles on an atom chip, where each qubit is carried by an atomic ensemble instead of a signal atom, by taking advantage of the Rydberg dipole blockade mechanism [20–23]. Comparing with the existing schemes, including both quantum gates with an atom chip and Rydberg state QC [10,15–18,20,22–26], our work has several advantages: (1) an array of atomic assembles can be easily realized on an atom chip; (2) the qubits have long coherence time through encoding them in the internal ground states; (3) the lifetime and sensitivity to the environment of the Rydberg state is not essential because it is just an assistant state and not the encoding state in the gate implementation; and (4) the phase of dipole interaction between the two qubits does not need to be controlled since the controlled not gate (CNOT) can be directly realized.

The basic element of the present scheme is the one-dimensional or two-dimensional atom lattices on an atom chip, which has already been proposed and demonstrated [27–29]. Here, we focus on a one-dimension atomic lattice. As shown in Fig. 1, microwires on a double layer atom chip can form the magnetic lattice. U-shaped magneto-optical traps can be used to cool and trap the atoms directly from the background vacuum environment at first. Then the cold atoms can be transferred to the corresponding Ioffe-Pritchard trap just by controlling the current flowing direction of the wires marked by "b" in Fig. 1 [30]. Thus thousands of cold atoms can be captured in each trap. The surface evaporating cooling or radio frequency evaporating cooling techniques can be applied to control the amount of atoms in each trap and the dimension of the traps [31,32]; and hence enters the single atom Rydberg blockade region where one Rydberg atom is enough to prevent the excitation of all other atoms in the ensemble. In this case, the energy level of the Rydberg excited atom is shifted away with several micrometers by the dipole-dipole interaction [21,33,34].

In a single magnetic trap, two hyperfine or Zeeman sublevels of electronic ground states of alkali atoms can be selected for the implementation of QC. As shown in Fig. 2, suppose $|a\rangle$ and $|b\rangle$ are two such internal ground states; then state $|a\rangle$ is used as a reservoir state for the atoms and state $|b\rangle$ is used to represent the quantum states; we can define that the quantum state $|0\rangle=|b,1\rangle$ and the quantum state $|1\rangle=|b,0\rangle$, where $|b,1\rangle$ is the collective symmetric state with only one excited atom in the internal ground state $|b\rangle$ and $|b,0\rangle$ is the collective symmetric state with all the atoms in the internal ground state $|a\rangle$ [25,26]. This encoding scheme means that an atomic assemble instead of a single atom can be applied to implementing QC.

The Rydberg blockade mechanism is applied to implement the states initialization as well as the gates. The initial state $|b,0\rangle$ can be prepared by optically pumping all atoms to

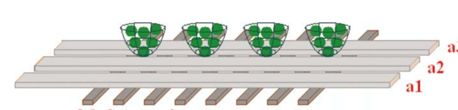

FIG. 1. (Color online) Setup of a one-dimensional atom lattice on an atom chip for the quantum computation.

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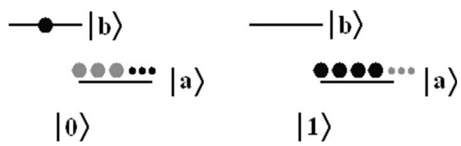

FIG. 2. Scheme of the qubit encoding, state $|0\rangle$ is carried by the collective symmetric state with one atom in state $|b\rangle$, and state $|1\rangle$ is the state with all the atoms in state $|a\rangle$.

state $|a\rangle$; and the preparation of state $|b,1\rangle$, that needs a single atom state producing process by the Rydberg blockade mechanism, is more complicated than that of a single atom QC scheme. As shown in Fig. 3(a), a single atom can be excited to the Rydberg state $|e\rangle$ by a short wavelength laser pulse through the Rydberg blockade mechanism at first, then another laser pulse pumps this single atom from $|e\rangle$ down to the ground state $|b\rangle$. This is the main and basic idea in our QC scheme. The detection of the ground state $|b\rangle$ could readout the encoding quantum information of the qubit.

After initializing the quantum states, one and two qubit gates can be implemented in this system. For example, the Hadamard gate can be realized by three laser pulses, as shown in Fig. 3(b). First of all, a π pulse couples the state $|b\rangle$ to the Rydberg state $|e\rangle$; then a $\pi/2$ pulse couples the state $|e\rangle$ to the state $|a\rangle$ to prepare the state $|e\rangle$ in a coherence superposition with 50% probability having one atom and 50% probability having no atom $(\frac{1}{\sqrt{2}}|e,1\rangle \pm \frac{1}{\sqrt{2}}|e,0\rangle)$; at last, another π pulse transfers the state $\frac{1}{\sqrt{2}}|e,1\rangle \pm \frac{1}{\sqrt{2}}|e,0\rangle$ to the ground state $\frac{1}{\sqrt{2}}|b,1\rangle \pm \frac{1}{\sqrt{2}}|b,0\rangle$, thus a Hadamard gate is achieved. In fact, arbitrary coherence superposition $(\alpha|b,1\rangle + \beta|b,0\rangle)$ in the Bloch sphere of the qubit can be realized with the same pulse sequences. Here, we assume that all the manipulations are in coherence.

As a two qubit gate, the CNOT gate can also be realized through the dipole-dipole interaction of the Rydberg atoms. As shown in Fig. 4, the gate can be implemented with five laser pulses. One pair of the pulses couples the control qubit and the other pulses couple the target qubit. First, a π pulse couples the state $|b\rangle$ to the Rydberg state $|e\rangle$ in the control qubit; second, a π pulse couples the state $|b\rangle$ to the unshifted Rydberg state $|e\rangle$ in the target qubit; third, another π pulse

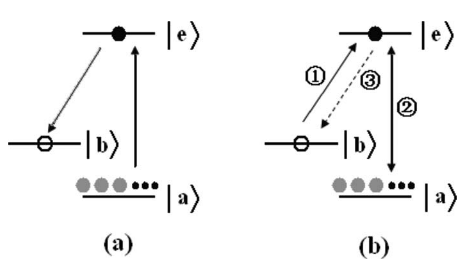

FIG. 3. (a) Scheme of the initial state preparation; a single atom is excited to the Rydberg state $|e\rangle$ by a laser pulse at first through the Rydberg blockade mechanism; then another laser pulse pumps the atom down to the state $|b\rangle$. (b) Scheme of one qubit gate implementing: (1) a π pulse couples the state $|b\rangle$ to the Rydberg state $|e\rangle$; (2) a $\pi/2$ pulse couples the state $|e\rangle$ to the state $|a\rangle$ to prepare the state $|e\rangle$ in a coherence superposition; and (3) another π pulse transfers the state $|e\rangle$ to the state $|b\rangle$.

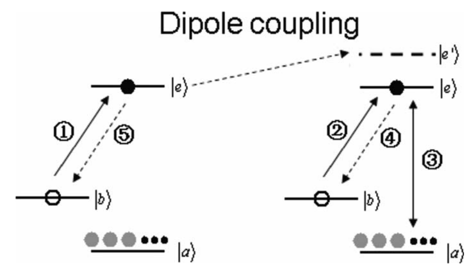

FIG. 4. Scheme of a CNOT gate implementation: (1) a π pulse couples the state $|b\rangle$ to the Rydberg state $|e\rangle$ in the control qubit; (2) a π pulse couples the state $|b\rangle$ to the unshifted Rydberg state $|e\rangle$ in the target qubit; (3) another π pulse couples the state $|a\rangle$ to the unshifted Rydberg state $|e\rangle$ in the target qubit; (4) a π pulse transfers the state $|e\rangle$ to state $|b\rangle$ in the target qubit; and (5) another π pulse transfers the state $|e\rangle$ to state $|b\rangle$ in the control qubit.

couples the state $|a\rangle$ to the unshifted Rydberg state $|e\rangle$ to reverse the quantum state in the target qubit; fourth, a π pulse transfers the unshifted Rydberg state $|e\rangle$ to state $|b\rangle$ in the target qubit; finally, another π pulse transfers the state $|e\rangle$ to state $|b\rangle$ in the control qubit. If the control qubit is $|b,0\rangle$, there will be no atom excited to the Rydberg state at the first π pulse in the control qubit. Then the Rydberg state does not shift in the target qubit, so a π pulse coupling the ground state $|b\rangle$ and the Rydberg state $|e\rangle$ on the target qubit will reverse the quantum states $|b\rangle$ and $|e\rangle$, so do the other two π pulses. If the control qubit is $|b,1\rangle$, there will be one atom excited to the Rydberg state under the first π pulse in the control qubit. Then the Rydberg state is shifted in the target qubit, so the three pulses are far detuned between the ground state and the shifted Rydberg state, and hence the target qubit will keep unchanged. In other words, the excitation of the Rydberg state from a logical $|0\rangle$ in the control qubit prevents the resonant driving of the atom in the target qubit and the corresponding flip operation; the nonexcitation of the Rydberg state from a logical $|1\rangle$ in the control qubit allows the flip operation in the target qubit. Thus the CNOT gate

$$\begin{aligned} |0\rangle|0\rangle &\rightarrow |0\rangle|0\rangle \\ |0\rangle|1\rangle &\rightarrow |0\rangle|1\rangle \\ |1\rangle|0\rangle &\rightarrow |0\rangle|1\rangle \\ |1\rangle|1\rangle &\rightarrow |1\rangle|0\rangle \end{aligned} \quad (1)$$

is realized directly.

Now, we consider rubidium (Rb) atoms for a specific implementation of the above ideas. On the atom chip, only the weak-field seeking atoms can be trapped by the magnetic field. For the ^{87}Rb atoms, the hyperfine levels $|F=2, m_F=1\rangle$ and $|F=1, m_F=-1\rangle$, whose magnetic moments and the corresponding static Zeeman shifts are approximately equal, gaining the smallest magnetic induced decoherence, can be selected for the two internal ground states $|a\rangle$ and $|b\rangle$. State $|a\rangle$ can be used to hold all the atoms and state $|b\rangle$ can be used to encode $|0\rangle$ and $|1\rangle$ of the qubit, respectively. The coherence time of this system has proved to be longer than 1 s

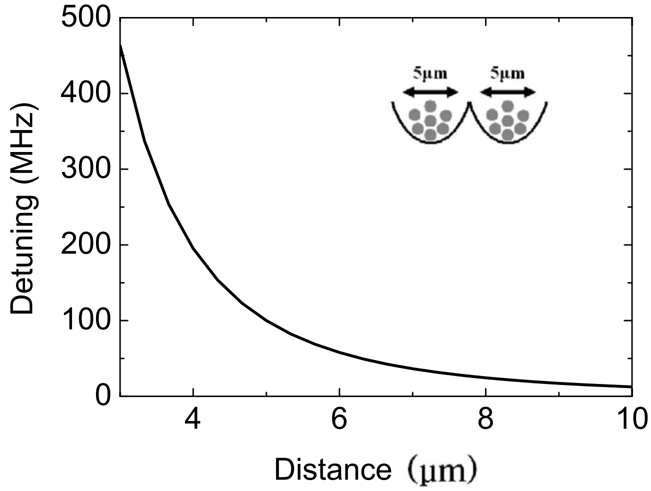

FIG. 5. Energy shift for the Rydberg state with $n=70$ vs dipole-dipole separation.

[35], which is long enough for the gate operations [10,20,26]. The two ground states are separated by 6.8 GHz, which is big enough for the selected exciting to the exact Rydberg state. Thus the Rydberg state can be excited by one photon or two photons easily. Here we choose $n \sim 70$ as the state $|e\rangle$. The coherence operation between the ground state and the Rydberg state with a laser is possible [36]. The dipole-dipole interaction of the Rydberg states of Rb, enhanced by "Fôster" processes, can be determined by [37]: $U=\frac{\delta}{2} \pm \sqrt{(\frac{\hbar\delta}{2})^2+\frac{4}{3}\frac{C_3^2}{r^6}}$, with δ an effective average two atom energy defect and $C_3=\frac{e^2}{4\pi\varepsilon_0}\langle np\|r\|ns\rangle\langle(n-1)p\|r\|ns\rangle$. The shift can be as large as 2 MHz when the atoms are 10 μm apart from each other and 100 MHz when the atoms are 5 μm apart from each other, as shown in Fig. 5. If $\Omega_i \ll U$, where Ω_i is the Rabi frequencies between the Rydberg state $|e\rangle$ and ground state $|a\rangle$ (or $|b\rangle$), then the shifted energy is big enough to blockade the exciting in the CNOT gate implementation and the doubly excited Rydberd states will never be populated simultaneously; and hence this scheme will be weakly sensitive to the exact distance between the atoms and the fluctuation of the atom numbers for its small phase accumulation during the gate operation [10]. The time needed for the gate operation is $\Delta t \approx 2\pi/\Omega_1 + 3\pi/\Omega_2$. Considering $\gamma \ll \Omega_i$, where γ is the loss rate of the Rydberg state, then the loss from the Rydberg state during the operation can also be neglected.

Compared to the single atom QC schemes, our proposal has two disadvantages. The interaction between the atoms in an ensemble will affect the coherence time of the entangled superpositions and the coherence coupling of the ground state with the Rydberg state. However, the collective dephasing rates are equal to the single atom rate due to the symmetry of the logical states we used [25,26]. The last assumption can be well-justified if the average interatomic distance is larger than the reduced optical wavelength $\lambda/2\pi$ [20]. Considering $N \approx 10^4$ atoms are trapped in a single trap, whose dimension is 5 μm, the distances between the nearest neighbors are also 5 μm (center to center). The atoms in an ensemble will enhance the blockade effect by $\sqrt{N}$ (N is the total atoms) but will not dephase the system $[N/V < (2\pi/\lambda)^3]$. The effect of the atom number fluctuations (ΔN) is negligible for $\Delta N/N \ll 1$. As shown in Fig. 6, the fidelity of the one and two qubit gate implementing can be as high as 100% [10,20,26,36].

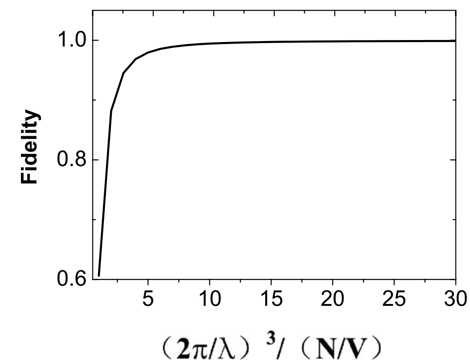

FIG. 6. Fidelity of the CNOT gate vs $(2\pi/\lambda)^3/(N/V)$.

We discussed here a QC implementation scheme on the atom chip trap, in fact another atom trap system can also be used, such as an optical lattice and plasmon atom trap lattice [38–40].

In conclusion, we have proposed an approach to a quantum computer with atomic ensembles on an atom chip by applying the Rydberg blockade mechanism. Both single atom and collision phase are no longer required. All the techniques are approachable in experiments. Thus the scheme has high experimental feasibility based on the current laboratory technique. In addition, this physical system can also be used to realize a one way quantum computer [41].

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