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RESEARCH ARTICLE

Quantum state manipulation of single-Cesium-atom qubit in a micro-optical trap

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Based on single Cesium atoms trapped in a 1064 nm microscopic optical trap we have exhibited a single qubit encoded in the Cesium "clock states". The single qubit initialization, detection and the fast state rotation with high efficiencies are demonstrated and this state manipulation is crucial for quantum information processing. The ground states Rabi flopping rate of 229.0 ± 0.6 kHz is realized by a two-photon Raman process. A clock states dephasing time of 3.0 ± 0.7 ms is measured, while an irreversible homogeneous dephasing time of 124 ± 17 ms is achieved by using the spin-echo technique. This well-controlled single atom provides an ideal quantum qubit and quantum node for quantum information processing.

Keywords qubit, single atom, Rabi flopping, spin-echo, dephasing time

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1 Introduction

In recent years, quantum information processing (QIP) has attracted intense attention [1]. The basic unit for QIP is a qubit encoded in an isolated two-level quantum system on which one can perform arbitrary single-qubit unitary operations. A number of different quantum systems [2–5] are currently being pursued to act as qubit such as trapped ions, nuclear spins, single photons, solid state Josephson junctions, quantum dots and trapped neutral atoms. Compare to other systems, qubits encoded in the ground states of laser-trapped neutral atoms are free of interactions with phonons and they are insensitive to external electric field. More importantly the stable and clean ground states provide long coherence time in room temperature. On the other hand, strong interaction between neutral atoms and external electromagnetic field provides convenient ways to manipulate both internal and external atomic states. Single atom can be confined in a small region and cooled to its vibrational ground state by means of laser cooling, far-off resonant trap (FORT) and sideband cooling [6, 7]. Other techniques of optical pumping, Raman process, microwave interaction and resonant fluorescence provide methods for initializing, rotating and reading the atomic qubit with high accuracy. Moreover, multiqubit operations could be performed based on dipole-dipole interactions between highly excited Rydberg atoms [8–10], cavity-mediated photon exchange [11] and controlled ground-state collisions [12]. All these developments and the related techniques have helped to bring about the single neutral atoms being a powerful candidate for QIP.

Single atom is usually obtained by loading it to a microsize dipole trap directly from a magneto-optical trap (MOT) by the light assistant blockade effect [13, 14] or transferring from a single atom mini-MOT [15, 16]. The ground "clock state" or other certain Zeeman states are usually used as the base states for a qubit. Due to the fluctuation of the surrounding magnetic field, differential optical AC Stark shifts and other dephasing factors [17] the decoherence time of the qubit is usually limited to microsecond scale in Zeeman states [18] or millisecond scale for hyperfine states [17].

In this paper we describe the trapping of single Cesium atoms in a 1064 nm red-detuned optical tweezer and the corresponding state manipulation as a qubit. In our experiment the qubit basis states are the "clock states" with $|0\rangle \equiv |F=4, m_F=0\rangle$ and $|1\rangle \equiv |F=3, m_F=0\rangle$. By optical pumping the single trapped atoms are initialized to state $|0\rangle$ and a two-photon Raman process is used for driving the states flopping. A Rabi flopping rate

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of 229.0 ± 0.6 kHz is observed, thus an arbitrary single qubit rotation can be realized by using a well-controlled Raman pulse. By applying two $\pi/2$ pulses with an adjustable time interval T a Ramsey spectroscopy is obtained and the corresponding dephasing time of 3.0 ms is extracted. By adding a π pulse between these two $\pi/2$ pulses the inhomogeneous dephasing can be recovered, which gives an irreversible dephasing time of 124 ms.

2 Quantum state manipulation of single-Cesium-atom qubit in a micro-optical trap

2.1 Single atom loading

The experimental setup is shown in Fig. 1. The details of the experimental setup were described in reference [19]. We started with a standard MOT which is loaded from a background vapor in an ultrahigh vacuum cell. When the MOT loading is finished a 5 ms polarization gradient cooling (PGC) phase is applied. A micro-size FORT is built up by a 1064 nm laser with beam waist of 2.1 μm, which is produced by an objective with high numerical aperture (NA = 0.29 and f = 36 mm, Alt lens) [20]. The FORT is overlapped with the atomic could in order to load atoms. The trap depth is about 1.3 mK corresponding to 38 mW of the FORT laser beam. With proper atomic loading rate only single atoms can be eventually trapped in the trap due to collisional blockade effect [14]. The photons from the trapped atom are then collected by the same objective system, which are separated from FORT beam by a dichromic cube, and they are coupled to a single photon counter (SPCM-AQRH-15-FC-17556, PerkinElmer Optoelectronics) through a single mode fiber.

A typical recorded photon count signal with 50 ms bin time of photon counter is shown in Fig. 2(a). Figure 2(b) gives the corresponding histogram. We can see that there is no 2-atom event for the loading process and the single atom loading probability is around 50% which consists with the theoretical maximum loading rate by using red-detuned assistant beam [14]. The result of Fig. 2(b)

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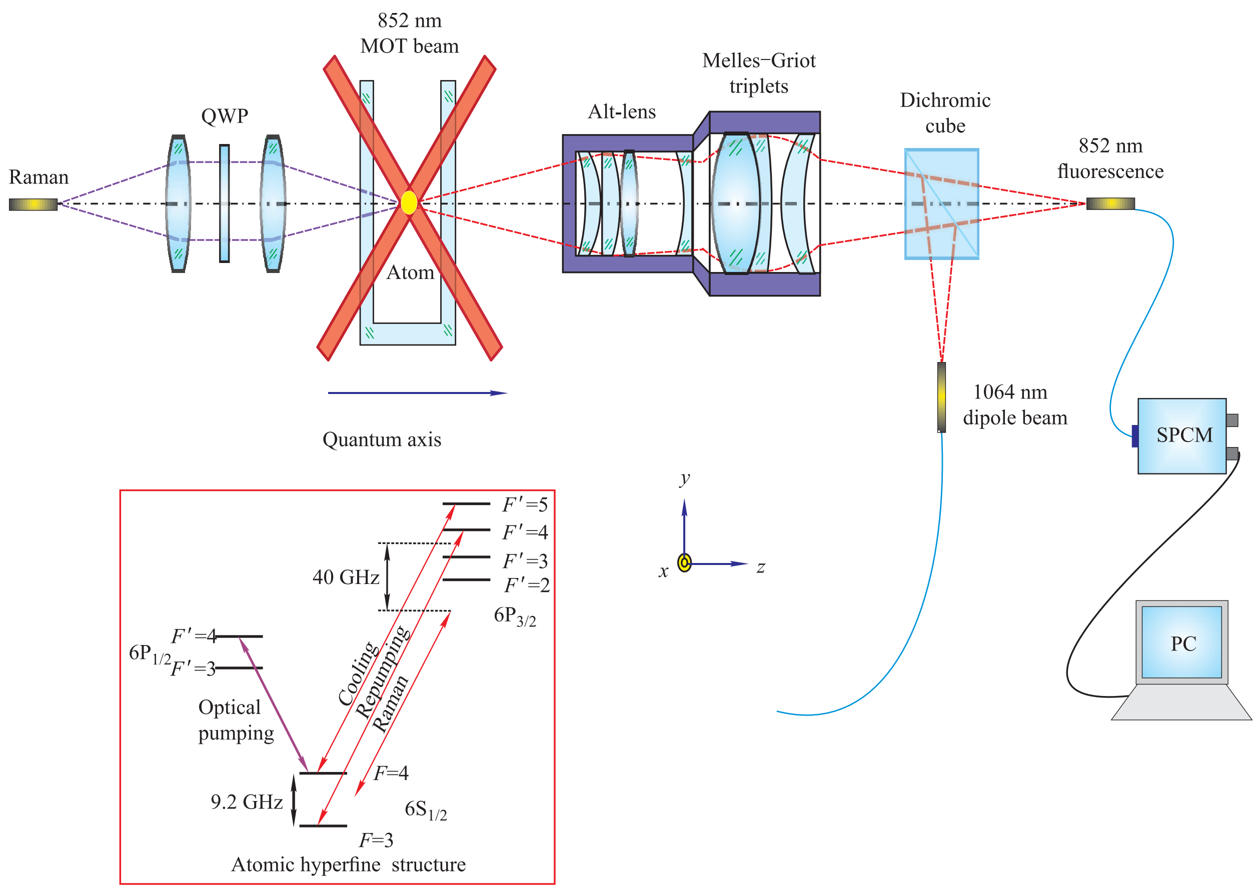

Fig. 1 The experimental setup. A tightly focused beam (FORT beam) by Alt-lens overlaps exactly with the MOT. Fluorescence light scattered by the trapped atom is collected by the same objective and separated from the FORT beam by a dichromic cube. The quantization axis is defined by a 2 Gauss magnetic field along the z axis. The inset shows the relevant atomic hyperfine structure of ^{133}Cs and the corresponding driving beam used to manipulate the single-atom qubit.

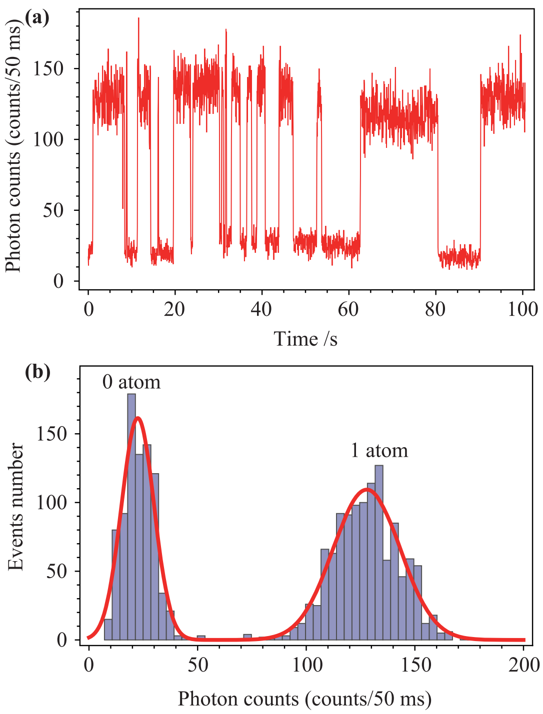

Fig. 2 Typical signal from single atoms. **(a)** Fluorescence recorded by the single counter and **(b)** the corresponding histogram.

shows that the two peaks of 1-atom and background are clearly separated and the corresponding countings are 125 counts/50 ms and 25 counts/50 ms, respectively. If we choose 65 counts/50 ms as the discrimination number, the events of background and 1-atom can be discriminated with an accuracy of 99.9%, which provides the upper bound of the hyperfine state detection fidelity by using the "push-away" method [21]. The idea is to push the atom in $F = 4$ state out of the trap by using a single-resonant beam and then check if the atom still stays in the trap. If the atom stays in the trap then it is in state $F = 3$. Otherwise, it is in the state of $F = 4$.

When single atom loading is finished, the MOT beams are switched-off for 10 ms to dissipate atoms outside the trap region and then the trap depth is ramped down to 0.59 mK within 10 ms for PGC phase. Another 5 ms PGC phase is applied with cooling beam detuning of about −30 MHz. After these two-stage PGC phases the atom is cooled to 25 μK eventually. The lifetime of the single atom in the trap is about 6 seconds. The lifetime is mainly limited by the background vacuum pressure and by the parametric heating due to fluctuation of trap beams [22]. In principle by reducing the vacuum pressure to the level of 10^{-11} torr, the atom lifetime could be extended to 100 seconds [23, 24]. However, the single-atom-qubit dephasing time is on the sub-second level, the current trapping time has no impact on demonstrating the internal state manipulations. The oscillation frequencies of the single atom in the optical trap with 1.3 mK trap are 49.2 kHz and 4.2 kHz on radial and axial directions respectively, which is measured by modulating the depth of dipole trap.

2.2 Quantum state manipulation of single Cs atom

The state rotation between $|0\rangle$ and $|1\rangle$ states is then accomplished by a two-photon Raman process with a home-made Raman laser. The two Raman beams are intentionally 40 GHz red-detuned to the $6P_{3/2}$ state (see inset of Fig. 1). They are circular polarized and propagate into the vacuum chamber which is parallel to the quantization axis. The beam size at the trap is 20 μm, thus we expect a qubit rotation rate of 234.3 kHz when 114 μW of total power is applied.

The final atomic state is detected by the "push-away" method. The retention of the atom in trap after the push away phase reveals the population of atom in $|1\rangle$ state.

By varying the Raman pulse length and measuring the atom retention right after the push-out pulse, the atomic qubit rotation can be observed. Figure 3 shows the Rabi flopping of single atomic qubit. The flopping rate is 229.0 ± 0.6 kHz, which is consistent with the theoretical expectation. The maximum measured transfer probability from $|0\rangle$ to $|1\rangle$ is about 0.93, which is mainly limited by the optical pumping efficiency. The result shows that the lengths of $\pi/2$ and the π pulses for the atomic qubit are 2.2 μs and 4.4 μs, respectively. This fast state manipulation facilitates fast quantum processing. In order to get a higher state flopping rate, Raman beams with higher intensities are needed either by increasing the Raman beam power or decreasing the beam size. By this way a state manipulation rate over MHz could be achieved [25].

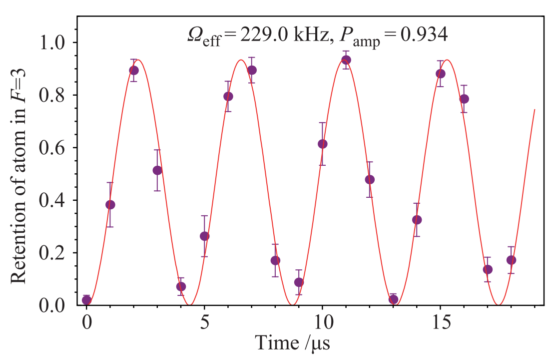

Fig. 3 Rabi flopping of single atomic qubit. The round points with error bars are experimental data. Each data point is obtained by the statistic over more than 80 samples and the range of error bars shown here is $\pm\sigma$. The red curve are the corresponding sine wave fitting, which gives a single qubit Rabi rotation rate of $2\pi \times (229.0 \pm 0.6)$ kHz.

2.3 Measurement of dephasing time

The qubit is subjected to the decoherences due to its interaction with the environment and it is characterized by spin relaxation T_1 and phase relaxation T_2. The spin relaxation time could be obtained by measuring the corresponding state lifetime. The data of the lifetime measurement is shown in Fig. 4 from which a 814 ± 56 ms T_1 time is extracted by the exponential fitting. The qubit phase coherence time T_2 is measured by Ramsey's interference. The atom is initially prepared in the state $|1\rangle$ and the first $\pi/2$ Raman pulse exactly drives the qubit in the state of $(|0\rangle + |1\rangle)/\sqrt{2}$. The system is then in a free evolution for a time of T and another $\pi/2$ pulse is applied to combine the two states and the states interferences can be measured, which is shown in the inset of Fig. 5. Figure 5 shows the evolution of the amplitudes of Ramsey interference with the time delay T. The qubit coherence time T_2 is thus determined as 3.0 ± 0.7 ms by fitting the data with an exponential function, which is basically typical for an atomic qubit trapped in a red-detuned FORT [25, 26].

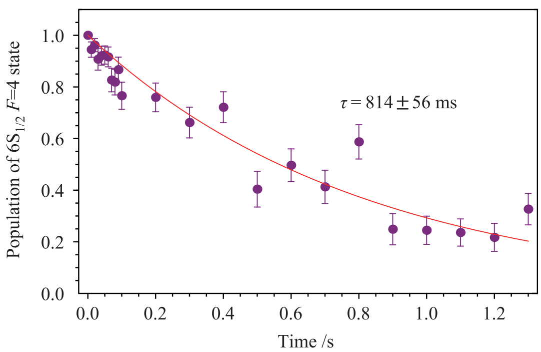

Fig. 4 Lifetime of the $6S_{1/2}$ $F = 4$ states, which gives the corresponding spin relaxation time of 814 ± 56 ms. The round points with error bars are experimental data. Each data point is obtained by the statistic over more than 80 samples and the range of error bars shown here is $\pm\sigma$. The red curve is the corresponding exponential fitting.

It is very useful to distinguish inhomogeneous from homogeneous effects in order to figure out where the decoherences come from [16]. The inhomogeneous dephasing (T_2^*) originates from the fluctuation of differential light shift between $|0\rangle$ and $|1\rangle$ when the atom moves in the FORT. For a red trap as we used, the atom is trapped in the position with strongest beam intensity and it has the largest light shifts. The two ground states (clock states) experience a differential ac stark shift as the atom oscillates in the trap and result in the inhomogeneous dephasing. In our experiment the differential ac stark shift can be estimated by $\delta_0 = \frac{\eta U_0}{\hbar} = -2\pi \times 3.9$ kHz with scaling factor $\eta = \frac{\omega_{hfs}}{\Delta_{hfs}} = 1.45 \times 10^{-4}$ and optical potential $U_0 = 1.3$ mK. This gives a theoretical dephasing time $T_2^* = 0.97 \times \frac{2\hbar}{\eta k_B T} = 4.1$ ms [17], which is consistent with our experimental result. In principle, this dephasing effect can be decreased if the atom is further cooled to low temperature and using a blue detuned trap [27, 28] or a magic polarization trap [29]. The homogeneous dephasing (T_2') is caused by several physical mechanisms including the beam intensity fluctuations, the fluctuations of the magnetic fields and some others, and these factors affect all the atoms in the same way [16]. The most important difference between these two dephasings is that the inhomogeneous dephasing is reversible while the homogeneous dephasing is irreversible.

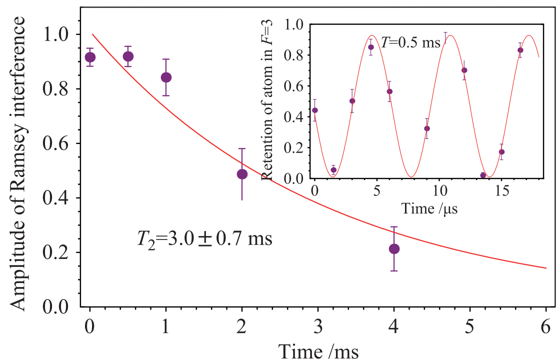

Fig. 5 The evolution of Ramsey fringe amplitude on time delay between two $\pi/2$ pulses. The round points with error bars are experimental data. Each point is obtained by the statistic over more than 80 samples and the range of error bars shown here is $\pm\sigma$. The red curve is the corresponding exponential fitting, which gives a single qubit coherence time of 3.0 ± 0.7 ms. The inset shows the Ramsey fringe around time delay $T = 0.5$ ms.

Spin echo technique [21], by applying a π pulse in the middle of the two $\pi/2$ pulses, can be used to recover the inhomogeneous dephasing and lengthen T_2. Figure 6 shows the spin echo data for our atomic qubit. As expected, the inhomogeneous dephasing is recovered by the π pulse. The observed fringe amplitude decreases much slower than that of Ramsey fringe. From the exponential fitting we could obtain the dephasing time as 124 ± 17 ms.

3 Conclusions and perspectives

In conclusion, based on single trapped cesium atoms in a micro-FORT, we have demonstrated quantum state initialization, detection and manipulation of the corresponding qubit encoded in the "clock state" with high efficiencies. The decoherence times are measured by Ramsey spectroscopy and spin-echo method. The measured decoherence time is much longer than the operation time of single qubit gate and it could be further improved by

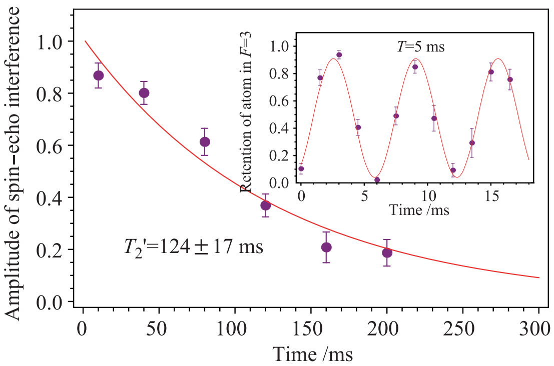

Fig. 6 The evolution of interference fringe amplitude of spin echo on time delay between two $\pi/2$ pulses. The round points with error bars are experimental data. Each data point is obtained by the statistic over more than 80 samples and the range of error bars shown here is $\pm\sigma$. The red curve is the corresponding exponential fitting, which gives a single qubit coherence time of 124 ± 17 ms. The inset shows the fringe around time delay $T = 5$ ms (the time interval between the first $\pi/2$ pulse and the π pulse).

increasing the single qubit transition efficiency and scale the single qubit to more. Such robust single qubit system implies a powerful competitor for QIP.

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