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Towards coherent manipulation of ground states of single cesium atom confined in a microscopic far-off-resonance optical dipole trap

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ABSTRACT

This work deals with the cooling and trapping of single cesium (Cs) atoms in a large-magnetic-gradient magneto-optical trap (MOT) and the confinement of single Cs atoms in a far-off-resonance optical dipole trap (FORT). The experiment setup is based on two large-numerical-aperture lens assemblies which allow us to strongly focus a 1064-nm TEM_{00}-mode Gaussian laser beam to a $1/e^2$ radius of ~ 2.3 μm to form a microscopic FORT for isolating single atom with environment and to efficiently collect the laser-induced-fluorescence photons emitted by single atoms for detecting and recognizing single atom's internal state. We have tried both of "bottom-up" and "top-down" loading schemes to confine single atoms in the microscopic FORT. In the "bottom-up" scheme, we have successfully prepared single Cs atoms in the MOT and transferred it into FORT with a probability of almost 100%. In the "top-down" scheme, we have achieved ~ 74% of single atom loading probability in the FORT using light-assisted collisions induced by blue detuning laser and with prepared many Cs atoms in the MOT. The relaxation time in hyperfine level of ground state of trapped single Cs atom is measured to be ~5.4 s. To coherently manipulate atomic quantum bits (qubit) encoded in the clock states ($m_F = 0$ states in $F_g = 3$ and 4 hyperfine levels) of single Cs atom via the two-photon simulated Raman adiabatic passage (STIRAP), we have prepared two phase-locked laser beams with a frequency difference of ~ 9.192 GHz by optically injecting an 852-nm master laser to lock the +1-order sideband of a 9-GHz current-modulated slave diode laser. The two phase-locked laser beams are used to drive STIRAP process in the Λ-type three-level system consists of Cs $|6S_{1/2}\ F_g = 4, m_F = 0\rangle$ and $|6S_{1/2}\ F_g = 3, m_F = 0\rangle$ long-lived clock states and Cs $|6S_{1/2}\ F_e = 4, m_F = +1\rangle$ excited state with the single-photon detuning of ~ -20 GHz. Rabi flopping experiments are in progress.

Keywords: single atom, far-off-resonance optical diploe trap (FORT), atomic qubit, laser cooling and trapping, coherent manipulation, phase-locked lasers with a large frequency deference, simulated Raman adiabatic passage (STIRAP)

1. INTRODUCTION

Scalable quantum bits (qubit) that can be prepared to arbitrary coherent superposition state are a basic component of quantum computer as described by DiVincenzo criteria [1]. Various physical system have been proposed as candidate for quantum computing research, such as neutral atoms, ions, photons, quantum dots, superconductor Josephson junction, color center in solid and so on. Among these cadidates, neutral atoms trapped in the confined space have emerged as one of the perfect cases [2-4] as the neutral atoms exhibit favorable properties for storing and processing quantum information. Single atoms trapped in far-off-resonance optical dipole traps (FORT) are hardly influenced by the electric and magnetic field so it is well isolated from their environment. Their hyperfine ground states can be prepared in pure quantum states including coherent superposition state with a long decoherence time. So it is promising carrier of quantum information processing. Using laser cooling techniques, countable numbers of neutral atoms can be cooled, confined, transported and manipulated. Several groups have successfully trapped single atom in a large-magnetic-gradient magneto-optical trap (MOT) or a FORT [3-6] with long lifetime. Using the single atom trapped in a FORT, the fast ground state manipulation of has been realized [7, 8]. Neutral atomic qubits have many progresses in quantum registers and quantum logic operations. With the help of the Rydberg blockade effect based on the long-range dipole-dipole interaction between two single atoms trapped in two FORTs separated from several micrometers, the entanglement between two neutral atoms [3] and two-qubit controlled-NOT (C-NOT) quantum gate [4] have been realized. 2D array of trapped atoms in a shift register based on 2D array of micro-lenses can be served as 2D quantum memory to archive and retrieve quantum information [9].

We have trapped single cesium (Cs) atoms in a large-magnetic-gradient MOT and transferred into a microscopic FORT [10, 11]. We can encoded quit in $|0\rangle = |6S_{1/2}\ F_g = 3, m_F = 0\rangle$ and $|1\rangle = |6S_{1/2}\ F_g = 4, m_F = 0\rangle$ clock states of single Cs

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atom trapped in our microscopic FORT. Our ongoing work is preparing the single atom in an arbitrary coherent superposition state of |10> and |1> states via the two-photon simulated Raman adiabatic passage (STIRAP), and further performing the Rabi flopping and evaluating decoherence time T_2*. Next, we will explore how does the effective temperature of single atoms in FORT affect decoherence time T_2* and how to further prolong T_2*.

2. EXPERIMENTAL SETUP FOR TRAPPING SINGLE ATOMS AND PHASE-LOCKED LASERS

2.1 Experimental setup for single-atom MOT and FORT

The experimental setup is shown in Fig.1, the cooling and trapping laser is generated by a grating extended-cavity diode laser (ECDL) (New focus DL100). In order to trap and cool atoms, the laser frequency has been stabilized to Cs $6S_{1/2}$ $F_g = 4$ - $6P_{3/2}$ $F_e = 5$ hyperfine transition by polarization spectroscopic (PS) scheme with certain frequency detuning (5~12 MHz red detuning from $F_g = 4$ - $F_e = 5$ hyperfine transition). The other laser beam is double-pass frequency shifted by the AOM_3 to serve as probe beam in the states preparation stage. The repumping laser is provided by another ECDL (not shown in Fig. 1) locked to $F_g = 3$ - $F_e = 4$ hyperfine transition.

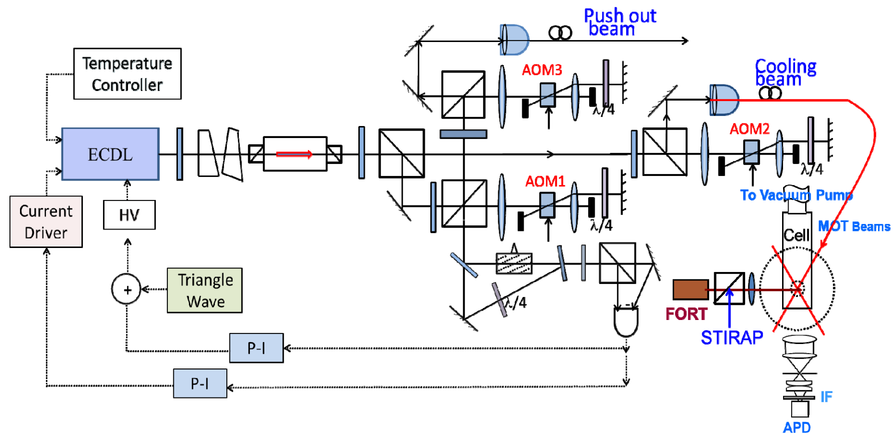

Fig. 1 Schematic diagram of experimental setup for single-atom MOT and FORT. Keys to figure: ECDL: external cavity diode lasers; P-I: proportion and integration amplifier; HV: high-voltage; λ/4: quarter-wave plate; AOM: acousto-optic modulator; FORT: far-off-resonance optical dipole trap; IF: interference filter; APD: avalanche photodiode.

As shown in the left side of Fig.1, the cooling and trapping laser is transferred to the MOT vacuum glass cell by a single-mode polarization- maintaining fiber. The repumping laser beam is coincided with the cooling and trapping laser beam by a polarization beam splitter (PBS) cube which is not shown in the Fig.1. The vacuum pump system (not shown in Fig. 1) is used to keep the pressure at 1×10^{-10} Torr ~ 2×10^{-11} Torr while the Cs atoms are released from atomic reservoir. Shown in the doted cycle, the two anti-Helmholtz magnetic coils which are installed above and beneath the glass cell are used to generate the large gradient magnetic field (~ 270 Gauss/cm) for single atom MOT. The FORT laser beam provided by a home-made 1064 nm single-frequency laser is strongly focused to a waist with the $1/e^2$ radius of ~ 2.3 μm by a large-numerical-aperture lens assembly to form a microscopic FORT for isolating single atom with environment. The laser power of 47 mW yields FORT's trap depth of ~ 1.5 mK. The single atoms are detected by counting the laser-induced-fluorescence (LIF) photons. The LIF photons from the atoms are collected with another lens assembly with a large numerical aperture of 0.29, which correspond 2% of whole 4π solid angle. An avalanche photodiode (APD) which works in photon-counting mode with typical quantum efficiency of ~ 50% at 852 nm is used to count LIF photons emitted by single atoms for detecting singe atom and recognizing single atom's internal state.

2.2 Experimental setup for phase-locked lasers for coherent manipulation of single atoms' ground state

In order to realize fast ground states manipulation of single Cs atom trapped in the FORT, we need to generate two phase-locked laser beams with the frequency difference of ~ 9.2 GHz (the hyperfine splitting of Cs $6S_{1/2}$ ground state) to drive the two-photon simulated Raman adiabatic passage (STIRAP) in the Λ-type three-level system consists of Cs $|6S_{1/2}$ $F_g = 4$, $m_F = 0>$ and $|6S_{1/2}$ $F_g = 3$, $m_F = 0>$ long-lived clock states and Cs $|6S_{1/2}$ $F_e = 4$, $m_F = +1>$ excited state with the single-photon detuning of ~ -20 GHz (see Fig. 9). We adopt an optical injection method to lock the +1-order sideband of the slave laser by the master laser when the slave laser is directly current modulated by a ~ 9-GHz radio frequency (RF) signal. The master laser is an 852-nm home-made ECDL with the typical output power of ~ 60 mW with typical linewidth of ~500 kHz (in 50 ms). The slave laser is another single-mode Fabry-Perot-type 9-mm-can-packaged AlGaAs diode laser with moderate output power (~100 mW). A part laser beam of the master laser with “S” polarization is optically injected into the slave laser. When the ~ 9.192 GHz RF signal with power of +15 dBm is added on the slave laser by a bias-T, we can injection lock the +1-order sideband by changing the current of the slave laser. At this time, the master and slave lasers have frequency difference of ~ 9.192 GHz. In order to verify the phase coherence between two lasers, we measured the beat-note signal between the master laser and the carrier of the slave laser. As shown in the top right side of Fig. 1, the master laser is shifted +100 MHz by an AOM to distinguish the beat note from the RF modulation frequency which is directly received by the fast photodiode. And the two lasers beams with the same polarization is detected by a fast photodiode and analyzed by a RF spectrum analyzer (Agilent E4405B). As shown in the lower right side in Fig. 1, the two phase-locked laser beams are superposed and then sliced by an AOM to control the timing and duration of the STIRAP pulses for coherent manipulation of single Cs atomic qubit.

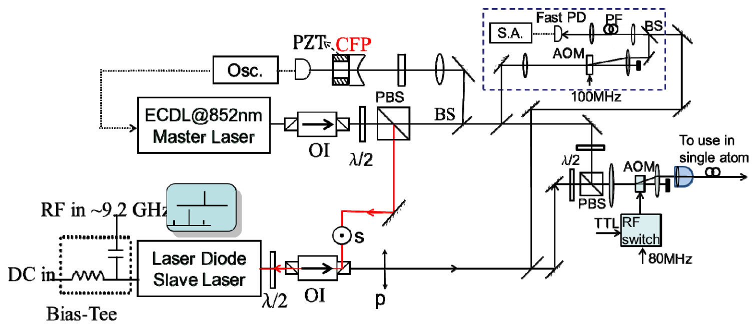

Fig. 2 Schematic diagram of experimental setup for two phase-locked lasers with a large frequency difference. Keys to figure: ECDL: extended-cavity diode laser; OI: optical isolator; λ/2: half-wave plate; PBS: polarization beam splitter cube; BS: beam splitter plate; CFP: confocal Fabry-Perot cavity; PD: photodiode; S.A.: RF spectrum analyzer; PF: polarization-maintaining fiber.

Fig. 3 (a) shows the beat note signal when the RF spectrum analyzer scans over 10 GHz and the resolution bandwidth (RBW) and the video bandwidth (VBW) are both set to 3 MHz. The peak at 9.293 GHz is the beat note between the master laser and the carrier of the slave laser. Fig. 3(b) shows the beat note signal when the RF spectrum analyzer scans over 100 Hz and VBW and RBW are both set to 1 Hz. The relative linewidth between the master laser and the carrier of the slave laser is ~1.02 Hz, which means that the two lasers are optical phase locked [6].

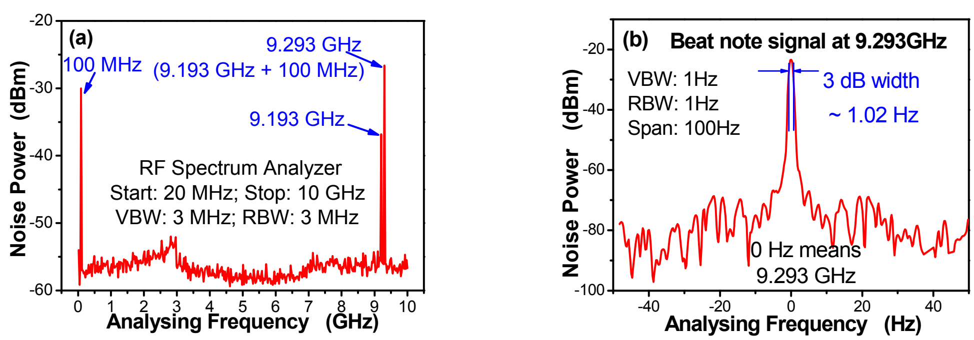

Fig. 3 (a) Beat-note signal measured by using the spectrum analyzer (Agilent E4405B). The start frequency is 20 MHz, while the stop frequency is 10 GHz, the resolution bandwidth (RBW) and the video bandwidth (VBW) are both set to 3 MHz. (b) Beat-note signal at ~9.293 GHz with the frequency span of 100 Hz, and RBW and VBW are both set to 1 Hz.

2.3 Experiment setup for single atomic qubit and coherent manipulation

To realize the Rabi flopping between |0> and |1> states, we first prepare single Cs atom in the $F_g = 4$ hyperfine state by first switching off the cooling beams then the repumping beams. As shown in Fig. 4, when the current is ~ 200 mA, the Helmholtz coil pair can generate ~ 1 Gauss magnetic field for providing the quantization axis. And a linearly-polarized (perpendicular to the quantization axis) Zeeman optical pump laser beam resonated with $F_g = 4$ - $F_e = 4$ hyperfine transition is used to prepare the single atom in |1> state. Then σ^{+}-circularly-polarized STIRAP laser pulse (along the quantization axis) is added. By changing the time duration of STIRAP pulse, single atom can be prepared in arbitrary coherent superposition states of |0> and |1> states. By measuring the population of single atoms in $F_g = 4$ states, we can demonstrate Rabi flopping between |0> and |1> states. Fig. 4 (b) shows the photo of our main experimental setup.

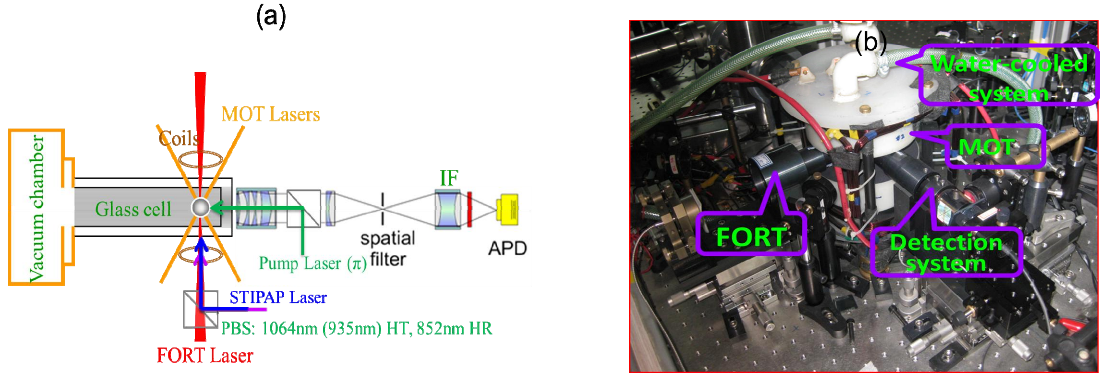

Fig. 4 (a) Schematic diagram for coherent manipulation of single atom trapped in the FORT. STIRAP lasers are the two phase-locked lasers with two-photon resonance but the single-photon detuning of ~ -20 GHz. The LIF photons emitted by single atom are collected with a collection efficiency of 2% and detected by an APD. (b) The photo shows the main parts of our singe-atom MOT and FORT.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 Preparing single atoms in FORT

In order to prepare single atomic qubit, at first we need to prepare single atoms in the FORT with long trapping lifetime. There are two schemes to load single atom into the FORT, one is called "bottom-up" scheme in which single atom is first prepared in the MOT and then transferred into the FORT, another is called "top-down" scheme in which first load many atoms from the MOT into the FORT and then using light-assisted collisions to decrease the number of atoms finally trapped in the FORT. In the "bottom-up" scheme, we have suppressed efficiently the loading rate of the MOT by operating in a very good vacuum condition (1×10^{-10} Torr ~ 2×10^{-11} Torr), reducing the diameter of laser beams (~ 2 mm), and increasing the gradient of quadrupole magnetic field (~ 270 Gauss/cm) [5]. We have strongly decreased the loading rate and have trapped few or even single atom in the MOT (as shown in Fig. 5 (a)). The transfer efficiency of single atom between the MOT and the FORT in our system is almost 100% (as shown in Fig. 5 (b)). By decreasing the vacuum pressure from ~ 1×10^{-10} Torr to ~ 2×10^{-11} Torr, we have improved the trapping lifetime of single atom from ~ 6.9 s to ~ 75 s [10]. By a 10-ms polarization gradient cooling phase, the trapping lifetime in the FORT can be extended to ~130 s [11].

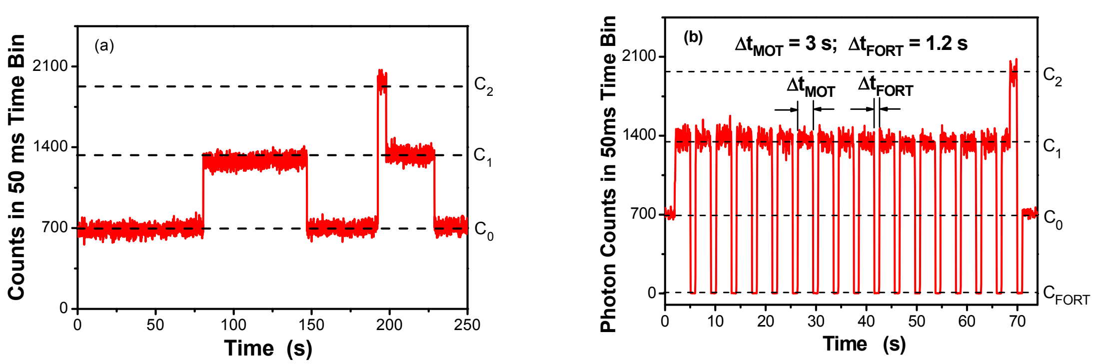

Fig. 5 (a) Typical LIF photon-counting signals for individual Cs atoms trapped in our large-magnetic-gradient MOT under optimized conditions. (b) Single atom is transferred between the MOT and the FORT with the overlap time of 25 ms. The LIF photon-counting levels of C_{FORT} indicate the fluorescence in the FORT, and C_0, C_1 and C_2, indicate there are no atom, one atom and two atoms trapped in the MOT, respectively. The time bin of APD is set to 50 ms.

In the "top-down" scheme, the atoms trapped in the FORT will undergo light-assisted collisions when resonate or near resonate laser exists. When using the blue detuned laser, we have increased the trapping efficiency of single atom up to ~ 74%, as shown in Fig. 6(a). This has proved possibility for loading 2D array of micro-FORTs for scalability. This point can be understood by light-assisted collisions [13], as shown in the Fig. 6 (b). Under the blue detuned laser, the atom pair is excited to a repulsive potential [13]. With proper blue detuning only one of the atoms will escape from the FORT after each inelastic collision [13], this has great enhanced the trapping efficiency of single atom, compared to the case of the red detuned laser [12] which has the maximum single-atom trapping efficiency of ~ 50% in the FORT.

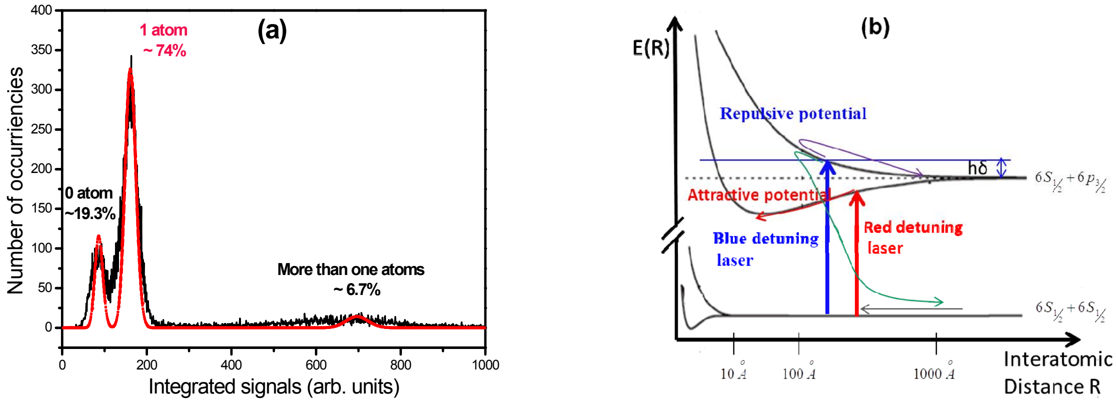

Fig. 6 (a) Atoms are trapped in the FORT with help of the blue detuned laser. (b) Simple model of light-assisted collisions. Grey arrow: two atoms in their electronic ground states approach each other. Red arrow: in the presence of red-detuned laser, the atom pair is excited to an attractive potential, leading to the pair loss. Blue arrow: in the presence of blue-detuned laser, the atom pair is excited to a repulsive potential. Purple arrow: an inelastic collision ensues, leading to the atom pair gaining a maximal h_δ in energy, followed by decay to the S + S state. Green arrow: optical shielding. When the light induces a transition each time the interatomic separation crosses R_c the collision is elastic.

3.2 The preparation and detection of the hyperfine state of single atoms

We have prepared single atom in the Zeeman states followed the timing sequence shown in Fig. 7. We first trapped single atoms in the MOT and then loaded them into FORT. In order to improve the loading efficiency, we reloaded the single atom between the MOT and FORT for twice. Just after single Cs atom loaded into the FORT, a 10-ms polarization gradient cooling phase with 0.28 times of MOT cooling laser's intensity is used to cool trapped single atom further. The single atoms have trapped in the FORT for ~ 130 s after polarization gradient cooling phase. By turning off the repumping laser 1 ms delay from the cooling laser, with the help of hyperfine optical pumping effect we can prepared single atom in the $F_g = 4$ hyperfine state (showing in the blue dash line of Fig. 7). A trigger signal is used to trigger the current of Helmholtz coil pair to generate the quantized axis with a magnetic field of ~ 1 Guass. The hyperfine states will split into several Zeeman sublevels due to Zeeman effect. The magnetic field quantization axis ensures that all of the $\Delta F = 1$, $\Delta m_F = 0$ transitions are distinguishable. The Zeeman optical pumping laser beam resonated with $F_g = 4 - F_e = 4$ hyperfine transition is applied for qubit initialization to |1> state. To detect the atom populated in Zeeman state, we use state-sensitive detection protocol by ejecting the atom in special hyperfine state from the trap.

We use a state-sensitive atom detection protocol for ejecting atoms from the FORT prior to the detect protocol. Specifically, we use a probe laser resonated with $F_g = 4$ - $F_e = 5$ transition, which is overlapped with one of the MOT cooling beams along Z axis to eject atoms residing in the $F_g = 4$ state. Therefore, any atoms observed during the subsequent detection protocol were occupying in the $F_g = 3$ ground state. Before adding the probe pulse, an arbitrary-wave function generator is used to control the V_a of the AOM for the FORT to decrease the FORT depth. The state-selective atom ejection relies upon the MOT laser system to detect if there are atoms in the MOT. By counting the transfer efficiency of single atom at difference FORT time, we have demonstrated preparing single Cs atom in the hyperfine states with the lifetime of ~ 5.4 s, as shown in Fig.8. The relaxation of hyperfine state is probably due to the Raman scattering of FORT laser and the collision effect between the atom trapped in FORT and background atoms.

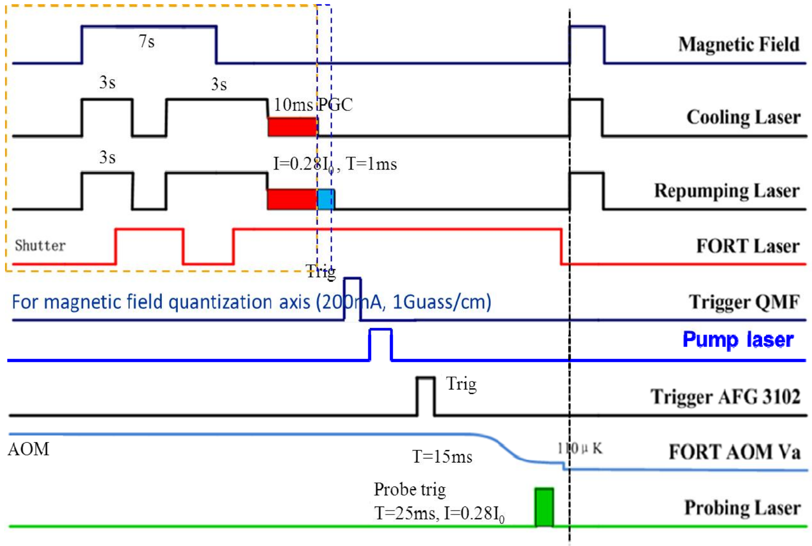

Fig. 7 The timing sequence for hyperfine level preparation and Zeeman state preparation and detection. The timing scheme in orange dash line is for the single atom trapping; the timing scheme in blue dash line is for the preparation of hyperfine state; the Trigger QMF is to trigger the magnetic file for providing the quantization axis; the Zeeman optical pumping laser is used to prepare the atom in |1> state; Trigger AFG 3102 is to trigger the arbitrary-wave function generator (Tek AG 3102) to control the V_a of AOM for FORT; the probe laser is to detected the preparation efficiency.

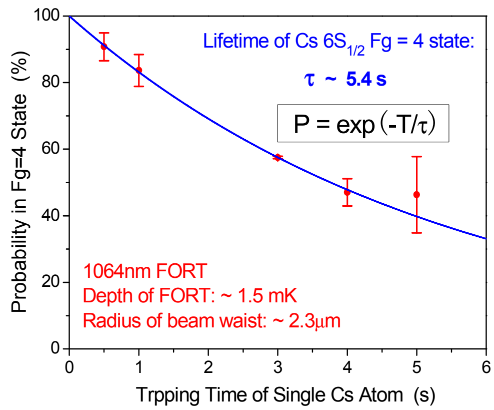

Fig. 8 Measured population probabilities of single Cs atoms in the Fg = 4 state after initial preparing.

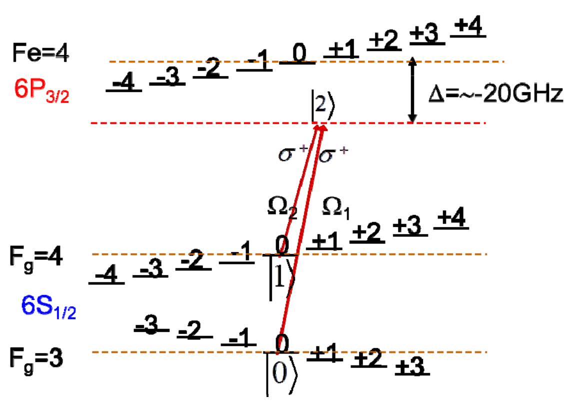

Fig. 9 STIRAP process for preparing coherent superposition state of |0> and |1> states. The two STIRAP lasers with σ^+ polarization are applied.

3.3 Towards coherent manipulation of single atomic qubit

Based on the single atom initialized in |1> state and the STIRAP lasers pulse, single atom can be prepared in arbitrary coherent superposition state $|\Psi\rangle = (\alpha|0> + \beta\ e^{i\varphi}|1>)$ $(|\alpha|^2 + |\beta|^2 = 1)$, which can severs as single atomic qubit. The qubits are the basic unit to realize quantum logic gate. Realization of single atom trapped in the FORT with long trapping lifetime and the two phase-locked lasers with one photon detuning of ~ -20 GHz and the two-photon resonance (Fig. 9) provide a solid basis for the coherent manipulation of single atomic qubit. By changing the STIRAP pulse's duration time, we expect that we can realize the coherent Rabi flopping and fast operation of atomic qubit soon.

4. CONCLUSIONS

In conclusion, we have efficiently prepared single atoms in the microscopic FORT with very long trapping lifetime (~ 130 s), and have initialized atomic qubit to |1> state (|0> state is also possible). Two phase-locked laser beams with frequency difference of ~ 9.192 GHz have been realized by optical injection method. Furthermore, we can locked the two lasers with – 20 GHz detuning from the Cs $6P_{3/2}$ F_e =5 state with help of a temperature stabilized etalon. Now this laser system is employed to drive the two-photon STIRAP in the Λ-type three-level system for further realization of coherent Rabi flopping between |0> and |1> states, fast operating atomic qubit, and evaluating the decoherence time T_2*. The experiment is in progress. Next step, we will explore how the effective temperature of single atoms in FORT affect the decoherence time T_2* and how to further prolong T_2*.

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