



Extending the coherence time limit of a single-alkali-atom qubit by suppressing phonon-jumping-induced decoherence

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In the fields of quantum metrology and quantum information processing with the system of optically trapped single neutral atoms, the coherence time of a qubit encoded in the electronic states is regarded as one of the most important parameters. A longer coherence time is always pursued for higher precision of measurement and quantum manipulation. The coherence time is usually assumed to be merely determined by the relative stability of the energy between the electronic states, and the analysis of the decoherence was conducted by treating the atom motion classically. We proposed a complete description of the decoherence of a qubit encoded in two ground electronic states of an optically trapped alkali atom by adopting a full description of the atomic wavefunction. The motional state, i.e., the phonon state, is taken into account. In addition to decoherence due to the variance of the differential light shift (DLS), a new, to our knowledge, decoherence mechanism, phonon-jumping-induced decoherence (PJID), was discovered and verified experimentally. The coherence time of a single-cesium-atom qubit can be extended to $T_2 \approx 20$ s by suppressing both the variances of DLS and PJID by trapping the atom in a blue-detuned bottle beam trap (BBT) and preparing the atom in its three-dimensional motional ground states. The coherence time is the longest for a qubit encoded in an optically trapped single alkali atom. Our work provides a deep understanding of the decoherence mechanism for single atom qubits and thus provides a new way to extend the coherence time limit. The method can be applied for other atoms and molecules, opening up new prospects for high-precision control of the quantum states of optically trapped atoms or molecules. © 2024 Optica Publishing Group under the terms of the [Optica Open Access Publishing Agreement](#)

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1. INTRODUCTION

The systems of optically trapped neutral single atoms are important platforms for quantum metrology [1–4], quantum measurement [5,6], quantum computation [7,8], and quantum simulations [9–11]. Usually, ground-state Zeeman sublevels, such as clock states, are adopted to encode the information as qubits for applications. The coherence time (T_2) of the qubit is thus one of the key factors for the high performance in these applications, and a long T_2 time is always pursued. To date, more than 30-s T_2 has been achieved for optically trapped single strontium atoms [2,12]. The coherence time is obtained by either using optical tweezers with a “magic wavelength” [2], where the differential light shift (DLS) between the two clock states can be cancelled, or nuclear spins [12]. Thus, coherence is intrinsically immune to fluctuations in the trapping light intensity.

However, for widely used alkali metal atoms, such as rubidium (Rb) atoms and cesium (Cs) atoms, the T_2 time of the qubit

encoded in the microwave clock states of optically trapped single atoms is much shorter due to the lack of a “magic wavelength”. The DLS between two clock states is susceptible to fluctuations in the trapping light intensity [13]. In recent years, many efforts have been made to improve the T_2 time of optically trapped alkali metal atoms by finding other “magic conditions” [14–24], where the first-order dependence of the DLS on fluctuations in light intensity and/or magnetic fields could be suppressed. By applying such “magic conditions”, the T_2 time can be improved from tens of milliseconds to the second level.

Another commonly adopted method for obtaining a long coherence time is to decrease the temperature of the trapped atom. In a full quantum picture where the vibrational quantum states (phonon states) are taken into account [25], a trapped single atom with a higher temperature has a wider population distribution on the phonon states. Due to the difference in the DLS associated with the different phonon states, the Ramsey signal is the sum of the interfering signals between the two atomic internal electronic

states associated with different phonon states, and a fast decay of the amplitude is observed, which is usually referred to as inhomogeneous decoherence. The inhomogeneous decoherence can be recovered by using a spin-echo technique [13,25]. Thus, the usually assumed residual decoherence factors [13], such as fluctuations in the trap depth, trap position, magnetic field, etc., will no longer depend on the atomic temperature. Moreover, without using “magic conditions”, a T_2 time of 12.6 s for single cesium atoms in blue-detuned traps was recently obtained [26] by adopting Carr-Purcell-Meiboom-Gill (CPMG) pulse sequences with the atom cooled to its ground phonon state. However, the decoherence mechanism associated with the atomic temperature has not been revealed.

In this article, we propose a mechanism of decoherence associated with the atomic temperature. This decoherence is caused by the stochastic jump of the atomic phonon state due to trapping noise. We therefore name this decoherence mechanism phonon-jumping-induced decoherence (PJID). To understand the PJID between the two internal electronic states $|a\rangle$ and $|b\rangle$, we have to take the external vibrational quantum states (phonon states) of the atom in optical traps into account of the full quantum wavefunction. The motion of the trapped atom in trap potentials caused by the light shifts of electronic states $|a\rangle$ and $|b\rangle$ is described by three-dimensional (3D) quantum harmonic oscillators. The motional evolution and the phonon jumping caused by the noise of the trapping field in the two trap potentials are independent because there is no interaction between the two internal states when the atom is freely evolving. Stochastic phonon jumping of the atom will induce decoherence between the two internal states $|a\rangle$ and $|b\rangle$. The PJID mechanism results in an exponential decay of coherence, which differs from the Gaussian decay of decoherence caused by the variance of the DLS. These two mechanisms occur simultaneously in the decoherence process. By examining the decoherence process of a Cs atom in a red-detuned optical trap with different intensity noise levels, we introduce PJID and show that experimental data are consistent with our model for PJID. After fully understanding the decoherence mechanisms, we adopt a blue-detuned BBT and cool the atom in its 3D motional ground states to suppress both the PJID and variance of the DLS. A coherent time T_2 of approximately 20 s for a qubit encoded in the clock states of a single trapped Cs atom is finally obtained. To the best of our knowledge, this is the longest coherence time for a qubit encoded in an optically trapped single alkali metal atom, and it can be improved further by improving the phase noise of the driving microwave, the pointing noise of the trap, etc.

2. PHONON-JUMPING-INDUCED DECOHERENCE

As shown in Fig. 1, the atom vibrational states (phonon states) are denoted by $|n_q\rangle$, where n_q is the phonon number (PN) along the vibrational axis q ($q = x, y, \text{ or } z$). The phonon states obey the orthogonal relation $\langle n_q | n'_q \rangle = \delta_{n_q, n'_q}$. In a rotating frame associated with the atom frequency between the qubit states $|a\rangle$ and $|b\rangle$, the time-dependent full wavefunctions of the atomic qubit can be expressed as $|\psi_a(t)\rangle = |a\rangle \otimes \prod_q |n_{q,a}\rangle$ and $|\psi_b(t)\rangle = \exp[-i(\Delta^{\text{DLS}}t + \phi)]|b\rangle \otimes \prod_q |n_{q,b}\rangle$. Here, $\Delta^{\text{DLS}} = -\eta \frac{U_0}{\hbar} + \frac{\eta}{2} \sum_q (n_q + \frac{1}{2})\omega_q$ is the DLS between states $|a\rangle \otimes \prod_q |n_{q,a}\rangle$ and $|b\rangle \otimes \prod_q |n_{q,b}\rangle$ [25], and ϕ is the additional phase. $\eta = |\frac{\omega_{\text{hfs}}}{\Delta}|$ is the ratio between the hyperfine splitting and the frequency detuning of the trap light. U_0 is the potential at the trap

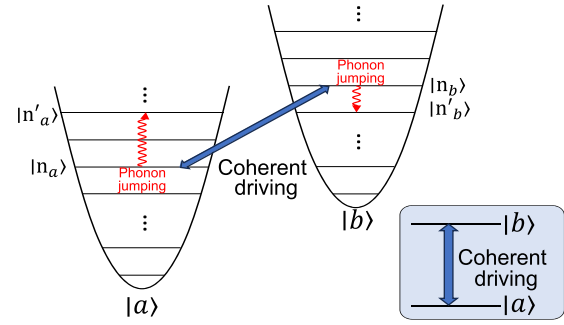


Fig. 1. Principle of PJID. The atom oscillates in the two optical traps produced by light shifts of the electronic states $|a\rangle$ and $|b\rangle$. The motional evolutions and the phonon jumpings caused by the noises of the trapping field in the two trap potentials are independent because there is no interaction between the two states when the atom is freely evolving. The phonon jumps induced by the noise of the trap light then destroy the coherence between the two electronic states. The coherence is usually characterized by the interference of the two states with the aid of coherent driving between the two electronic states with the same phonon number.

center, and ω_q is the oscillation frequency. The coherence between the two states is

$$C(t) = \int d\Delta^{\text{DLS}} \int d\phi f(\Delta^{\text{DLS}}) \varphi(\phi) \text{Tr}(|\psi_a(t)\rangle \langle \psi_b(t)|), \quad (1)$$

where $f(\Delta^{\text{DLS}})$ and $\varphi(\phi)$ are the probability distributions of Δ^{DLS} and ϕ , respectively. The trace is made over both the electronic and phonon state spaces. Then, it is rewritten as

$$C(t) = \int d\Delta^{\text{DLS}} \int d\phi f(\Delta^{\text{DLS}}) \varphi(\phi) e^{-i(\Delta^{\text{DLS}}t + \phi)} \prod_q \delta_{n_{q,a}, n_{q,b}}. \quad (2)$$

We first discuss the DLS-dependent part of Eq. (2), which can be separated as

$$C_1(t) = \int d\Delta^{\text{DLS}} f(\Delta^{\text{DLS}}) e^{-i\Delta^{\text{DLS}}t}. \quad (3)$$

For a given spatial structure of the optical trap, the potential U_0 and trap frequency ω_q are determined by the total trap power P . The probability distribution of P usually follows a Gaussian function $\exp[-(P - P_0)^2 / (2\sigma_P^2)]$ with P_0 and σ_P as the mean and root mean square (rms) values of the total trap power, respectively. The probability distribution of Δ^{DLS} also follows a Gaussian function with $f(\Delta^{\text{DLS}}) \propto \exp[-(\Delta^{\text{DLS}} - \Delta_0^{\text{DLS}})^2 / (2\sigma_{\text{DLS}}^2)]$, where Δ_0^{DLS} is the mean value of DLS. The variation in the DLS (σ_{DLS}) depends on σ_P by

$$\sigma_{\text{DLS}} = -\eta \frac{U_0}{\hbar} \frac{\sigma_P}{P_0} + \frac{\eta}{4} \sum_q \left(n_q + \frac{1}{2} \right) \omega_q \frac{\sigma_P}{P_0}. \quad (4)$$

By setting $C_1(0) = 1$, the decay of the coherence given in Eq. (3) will finally take a Gaussian form:

$$C_1(t) = e^{-\sigma_{\text{DLS}}^2 t^2 / 2}. \quad (5)$$

Next, we will discuss the rest of Eq. (2), which is connected to the stochastic phonon jumps induced by the noise of the trap light. As a consequence, the jump of either the PN or the phase would cause decoherence. We assume that the atom is initially prepared in a superimposed state of $|a\rangle \otimes \prod_q |n_{q,a}\rangle$ and $|b\rangle \otimes \prod_q |n_{q,b}\rangle$

with $n_{q,a} = n_{q,b}$ by a coherent driving field. Assuming that the PN associated with one electronic state alternates due to the noise at time t , according to Eq. (2), the coherence immediately collapses because $\delta_{n'_{q,a}, n'_{q,b}} = 0$ due to $n'_{q,a} \neq n'_{q,b}$. Here, $n'_{q,a}$ and $n'_{q,b}$ are the PNs at time t . Even if the PNs are alternated simultaneously to the same number ($n'_{q,a} = n'_{q,b}$) at time t , the coherence also disappears due to the stochasticity of the noise-induced phonon jumping process. In this case, the phase ϕ in Eq. (2) is evenly distributed in the range $[0, 2\pi)$ with $\varphi(\phi) = 1/2\pi$. Therefore, $\int_0^{2\pi} d\phi \varphi(\phi) = 0$ and the coherence is $C = 0$.

The process of decoherence is determined by the jumping rate of the PN. If we define the jumping rate from PN n_q along axis q as R_q , the probability of the atom being in state $|n_q\rangle$ is p_{n_q} . Then, p_{n_q} obeys the rate equation $\dot{p}_{n_q} = -R_q p_{n_q}$. Hence, the coherence takes the form

$$C_2(t) = e^{-(R_x + R_y + R_z)t}. \quad (6)$$

In an optical trap, phonon jumping is induced by the intensity noise and the beam-pointing noise associated with the trap light [27,28]. The intensity (beam-pointing) noise will cause the PN to jump by two (one). The overall phonon jumping rate (PJR) from state $|n_q\rangle$ is the sum of all the jumping rates given in [27,28], and the result is

$$R_q = \frac{\pi\omega^2}{8} S_k(2\omega_q)((n_q + 1)^2 - n_q) + \frac{\pi}{2\hbar} M\omega_q^3 S_q(\omega_q)(2n_q + 1), \quad (7)$$

where M is the mass of the trapped atom and ω_q is the trap frequency along the q axis. $S_k(\omega)$ and $S_q(\omega)$ are the one-sided power spectra of the fractional fluctuations in the spring constant and coordinate q .

Finally, we obtain the decay of the overall coherence

$$C(t) = C_1(t)C_2(t) = e^{-\sigma_{\text{DLS}}^2 t^2/2 - Rt}, \quad (8)$$

where $R = R_x + R_y + R_z$ is the overall phonon jumping rate (PJR). We see that the coherence actually shows a Gaussian and exponential combined decay. It should be noted that the above analysis is based on an atom with specific phonon number n_q . For a thermal atom the overall variation in the DLS and PJR should be obtained by $\sigma_{\text{DLS,all}}^2 = \sum_{n_q} P(n_q)\sigma_{\text{DLS}}^2$ and $R_{\text{all}} = \sum_{n_q} P(n_q)R$ with $P(n_q) = \langle n_q \rangle^{n_q} / (\langle n_q \rangle + 1)^{n_q+1}$ the probability of an atom on phonon state $|n_q\rangle$ and $\langle n_q \rangle$ the mean phonon number.

In the experiment of optically trapped single atoms, a trapping laser with low intensity noise and pointing noise is usually adopted to get a longer atom storage time and coherence time. In such situation, the PJID is much smaller than the DLS variance. To experimentally check the effect of PJID, we deliberately amplify the PJID by adding a 40-dB intensity noise on the trap light. We measured two coherence decays in a red-detuned ODT with a normal intensity noise and a deliberately enlarged intensity noise. It should be noted that the 40-dB noise will not affect the state lifetime T_1 , but the atom lifetime is reduced to approximate 1 s compared to the 30-s lifetime without the noise. The ODT is formed by strongly focusing a 1052-nm laser beam to a size of 1.65 μm and loading single Cs atoms from a magneto-optical trap (MOT). The coherence between the clock states ($|6S_{1/2}F = 3, m_F = 0\rangle$ and $|6S_{1/2}F = 4, m_F = 0\rangle$) was measured by a standard spin-echo interferometer [29,30] with a 9.2-GHz microwave driving field. Figures 2(a) and 2(b)

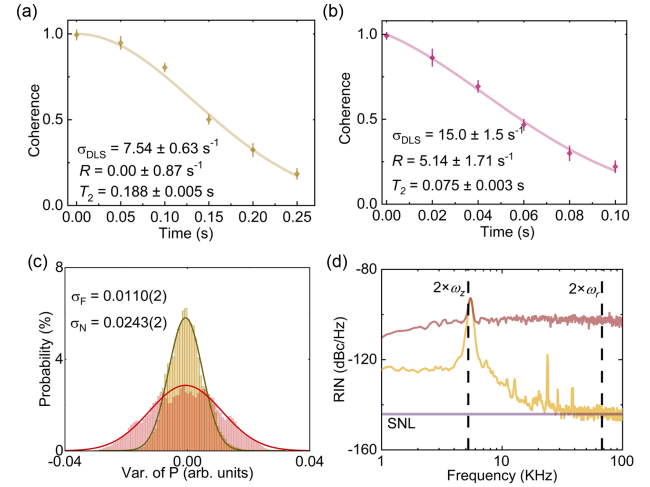


Fig. 2. Coherence decay of a single Cs atom trapped in a 1052-nm ODT. (a), (b) Coherence decays at the conditions that the laser is free running (low intensity noise) and 40-dB intensity noise is added. (c) Displays the distributions of the sampled light power, which is normalized to the mean value, for the two conditions. σ_F and σ_N are the normalized power variances for the free-running laser and laser with 40-dB noise added, respectively. (d) Displays the noise spectra, in which the dashed lines marked as $2 \times \omega_x$ and $2 \times \omega_r$ are the frequencies where the parametric process occurs. SNL: shot-noise limit.

show the coherence data for different time delays under the condition that the trap laser is free running and 40-dB intensity noise is added in a frequency range that covers the trap frequencies. In Fig. 2(a), the coherence decays more like a Gaussian function because of the low PJR. The data fitting by Eq. (8) gives a DLS variation of $\sigma_{\text{DLS}} = 7.54 \pm 0.63 \text{ s}^{-1}$ and a PJR $R = 0.00 \pm 0.87 \text{ s}^{-1}$. The corresponding $T_2 = 188 \pm 5 \text{ ms}$, which is defined by $1/e$ of the coherence. However, the coherence data in Fig. 2(b), where 40-dB intensity noise is added to the trap light, apparently deviate from the Gaussian function, and the $1/e$ coherence time is $T_2 = 75 \pm 3 \text{ ms}$. In this situation, Eq. (8) provides good data fitting, and the fitted DLS variation and PJR are $\sigma_{\text{DLS}} = 15.0 \pm 1.5 \text{ s}^{-1}$ and $R = 5.14 \pm 1.71 \text{ s}^{-1}$, respectively. Compared to the condition in which the laser is free running, the DLS variation is increased by a factor of two, which is in agreement with the increase (≈ 2.2) in the variance of the trap light intensity [Fig. 2(c)]. The PJR is increased by 5.14 s^{-1} , which comes from the parametric-process-induced phonon jumping [the first term in Eq. (7)] because the second term remains the same in the two situations. By using the measured intensity noise [Fig. 2(d)], the increase in the PJR can be estimated as 6.0 s^{-1} (Supplement 1), which agrees well with the number obtained by the data fitting. Therefore, the existence of PJID can be confirmed.

3. 20-s COHERENCE TIME OF A QUBIT ENCODED IN AN OPTICALLY TRAPPED SINGLE Cs ATOM

A long coherence time can be obtained by suppressing both the DLS variance and PJR. The DLS variance can be greatly suppressed by adopting red-detuned optical traps with “magic conditions” [14]. However, because the atom is confined in the region of intensity maxima, the decoherence induced by photon scattering is also maximized (Supplement 1). In a well-aligned blue-detuned trap, the atom is trapped in the region with zero light

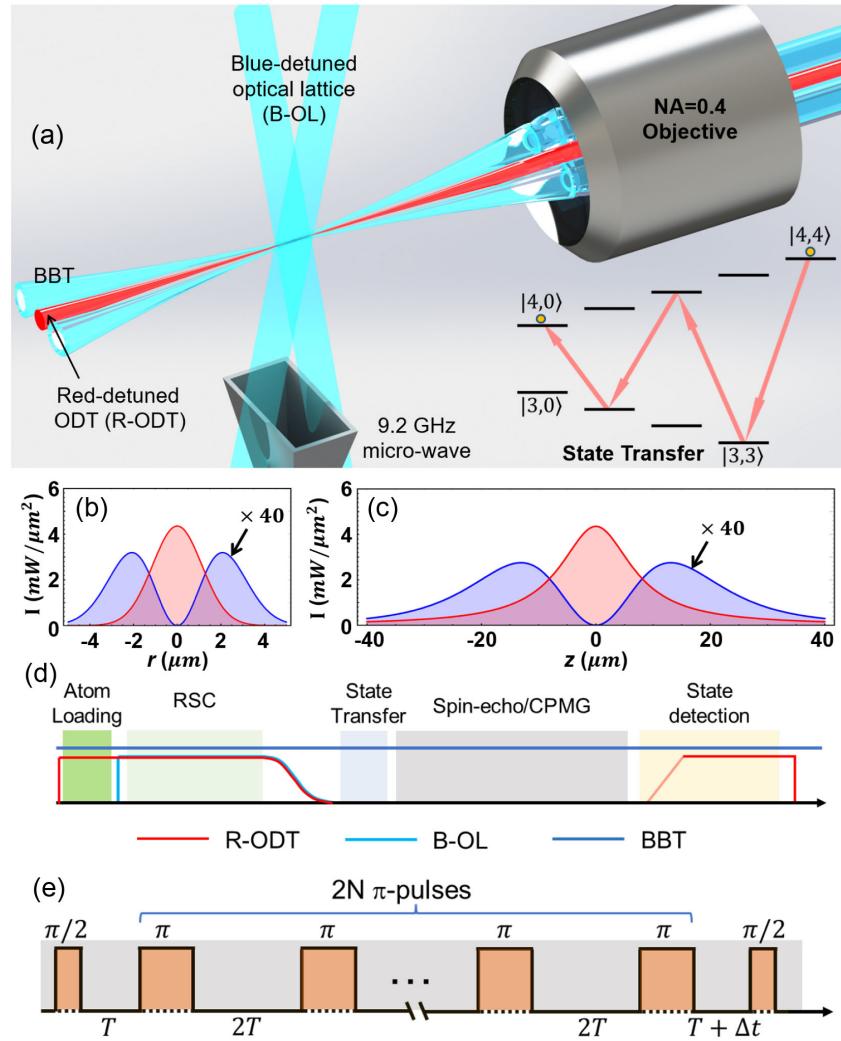


Fig. 3. (a) Schematic experimental setup for the long coherence time of a single Cs atom in a BBT. The R-ODT and B-OL combined trap is used for the motional ground state cooling of the atom by Raman sideband cooling. The state is transferred from $|6S_{1/2}F=4, m_F=4\rangle$ to $|6S_{1/2}F=4, m_F=0\rangle$ after the RSC by four π -pulses. (b), (c) Display the intensity profiles of the R-ODT and BBT along the radial and the axial directions, respectively. The BBT laser intensity is plotted with 40 times enlargement. (d) The time sequence for a single iteration of the experiment. (e) The Carr-Purcell-Meiboom-Gill pulse sequence used for suppressing the residual DLS variance.

intensity in principle. Thus, the decoherence induced by photon scattering is completely canceled. The main term of DLS [the first term on the right-hand side of Eq. (4)] also disappears. The rest of the DLS due to the phonon energy can be suppressed by preparing the atom in its three-dimensional (3D) motional ground state (zero phonon state, ZPS), i.e., $n_q = 0$.

As given by Eq. (7), the PJR is determined by the trap frequency ω_q , intensity noise S_k , pointing noise S_q , and PN n_q . Therefore, it can be suppressed by reducing these parameters. The trap frequency ω_q is determined by the depth and size of the optical trap and thus can be reduced by using a trap with shallow depth and large size. The intensity noise can be suppressed by applying a noise eater or adopting a low-noise laser. The pointing noise can be minimized by improving the mechanical stability of the trap optics. The most efficient way to suppress the PJR is to decrease the PN. PJID can be minimized by preparing the atom in its 3D ZPS.

Here, we adopt a blue-detuned optical bottle beam trap (BBT) to demonstrate the long coherence of a qubit encoded in a single Cs atom by suppressing both the DLS variance and the PJR. The trap is formed by focusing two parallelly propagating 780-nm

vortex laser beams with orthogonal polarization by a single objective with a numerical aperture $NA = 0.4$ [Fig. 3(a)]. Therefore, the two beams cross each other around the focus of the objective, and a microsized BBT is formed [31]. The radius and length of the BBT are $r = 2.9 \mu\text{m}$ and $l = 14.3 \mu\text{m}$, respectively. The details of the trap construction can be found in Supplement 1. The intensity ratio between the trap center and the trap barrier is 1.5%. Thus, the DLS variance can be greatly reduced by using a shallow trap depth and preparing the atom in its motional 3D ground states. The PJR can also be suppressed by adopting a low-intensity-noise laser and improving the mechanical stability of the trap. We use a 780-nm external-cavity diode laser to build the trap. The output has very low intensity noise [Fig. 4(b)], and the relative intensity variance is smaller than 0.015%. By using a trap power of 9 mW, we can build a trap with a minimum barrier of $k_B \times 50 \mu\text{K}$ (k_B is the Boltzmann constant). The trap frequencies are $(\omega_x, \omega_y, \omega_z) = 2\pi \times (5.65, 8.3, 0.435)$ kHz. For a Cs atom in its 3D ZPS, the estimated DLS variance and the PJR due to the intensity noise are $\sigma_{\text{DLS}} < 3.0 \times 10^{-3} \text{ s}^{-1}$ and $R_k < 2.5 \times 10^{-6} \text{ s}^{-1}$, respectively. The pointing noise of the BBT

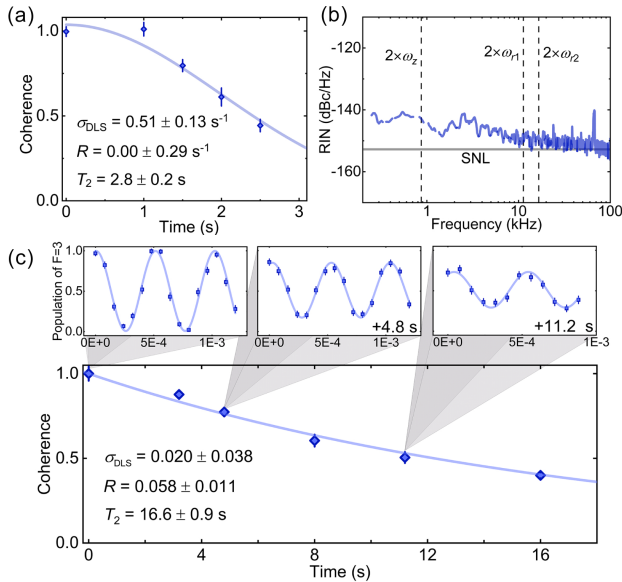


Fig. 4. Coherence decay of a single Cs atom in the 780-nm BBT. (a) Coherence decays obtained by spin-echo spectroscopy. (b) Relative intensity noise of the BBT trap light, and the dashed lines are the frequencies at which the parametric process occurs. SNL: shot-noise limit. (c) Coherence decay by CPMG sequence. Three interference fringes at time delays of 0, 4.8, and 11.2 s obtained by the CPMG sequence are also shown as insets.

is difficult to measure, and it is improved by mounting all the optics with the cage system from Thorlabs. With the atom in its 3D ZPS, the PJR due to pointing noise can also be minimized. Therefore, a long T_2 time is expected.

The single atom in its 3D ZPS is prepared with the aid of a combined microsized ODT. Due to the loose confinement of the atom in the BBT, it is impossible to directly cool the atom to its 3D ZPS. Therefore, an extra combined microsized ODT with strong confinement is adopted. The experimental sketch is displayed in Fig. 3(a), and the BBT and ODT are arranged to be overlapped in both the radial and axial directions [Figs. 3(b) and 3(c)]. The time sequence is shown in Fig. 3(d) and the experimental details can be found in Supplement 1. Resolved Raman sideband cooling (RSC) is used to prepare the atoms in 3D ZPS, and the residual phonon numbers are $(\bar{n}_x, \bar{n}_y, \bar{n}_z) \simeq (0.07 \pm 0.07, 0.04 \pm 0.04, 0.08 \pm 0.06)$ [32]. The atom populates on state $|6S_{1/2}F=4, m_F=4\rangle$ after the RSC process. The combined ODT is then adiabatically turned off, and the atom is resettled in the BBT without changing its phonon state and electronic state. The atom is transferred to $|6S_{1/2}F=4, m_F=0\rangle$ by four microwave π -pulses via the intermediate states $|6S_{1/2}F=3, m_F=3\rangle$, $|6S_{1/2}F=4, m_F=2\rangle$, and $|6S_{1/2}F=3, m_F=1\rangle$. A spin-echo between the Cs clock states ($|6S_{1/2}F=3, m_F=0\rangle$ and $|6S_{1/2}F=4, m_F=0\rangle$) is performed to evaluate the decay of the coherence.

The coherence decay measured by a spin-echo interferometer is displayed in Fig. 4(a). The data show a Gaussian function decay, and the fitting by Eq. (8) gives the DLS variance $\sigma_{\text{DLS}} = 0.51 \pm 0.13 \text{ s}^{-1}$ and PJR $R = 0.00 \pm 0.29 \text{ s}^{-1}$. The variation of DLS dominates the decay; thus the fitted R has a very large error and is inaccurate. The corresponding coherence time is $T_2 = 2.8 \pm 0.2 \text{ s}$. The DLS variance is much larger than we estimated. This is probably due to the slow disturbance of the

energy levels caused by the variations in the magnetic field and the BBT light field, which are not taken into account in the discussions above. A CPMG pulse sequence is then applied to decouple the spin dynamics from these slow disturbances [33,34]. The pulse sequence is shown in Fig. 3(e), where a series of π -pulses is inserted between the two $\pi/2$ -pulses. The time interval $T = 0.8 \text{ s}$ is chosen for its best performance. The CPMG pulse sequence works as a filter that can filter out slow DLS variations with frequencies $n \times 0.0625 \text{ Hz}$ ($n = 1, 2, 3, \dots$). The obtained decay of coherence turns out to be much slower. The data are shown in Fig. 4(c). The residual DLS variance and PJR are fitted by Eq. (8) with $\sigma_{\text{DLS}} = 0.020 \pm 0.038 \text{ s}^{-1}$ and $R = 0.058 \pm 0.011 \text{ s}^{-1}$. The variation of DLS σ_{DLS} is dramatically suppressed, and the PJID then dominates the coherence decay. The small DLS variance might come from residual variations in the magnetic field and BBT light. The stability and phase noise of the microwave source may also contribute to the DLS variance. The main source of the residual PJR should be the pointing noise of the BBT. All of these factors could be suppressed further by using proper methods. In the current case, the coherence time is $T_2 = 16.6 \pm 0.9 \text{ s}$. Accounting for the single atom lifetime of $105.5 \pm 13.1 \text{ s}$ (Supplement 1), the actual coherence time should be $T_2 = 19.7 \text{ s}$.

4. CONCLUSION

We discovered and experimentally verified a new decoherence mechanism, i.e., phonon-jumping-induced decoherence, for a single-alkali-atom qubit trapped in an optical dipole trap. Then, a coherence time of approximately 20 s is obtained for a qubit encoded in a single Cs atom by suppressing both the DLS variance and the PJID by adopting a blue-detuned BBT and preparing the atom into its 3D ZPS. This is the longest coherence time reported to date for a qubit encoded in an optically trapped alkali metal atom. Our analysis and the results and corresponding methods for improving coherence are universal and can be applied to other atoms and molecules, opening up new prospects for expanding the coherent manipulation of optically trapped atoms or molecules.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

Supplemental document. See Supplement 1 for supporting content.

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