Confinement and retrieval of local phonons in a trapped-ion chain

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Driving an ion at a motional sideband transition induces the Jaynes–Cummings (JC) interaction. This JC interaction creates an anharmonic ladder of JC eigenstates, resulting in the suppression of phonon hopping due to energy conservation. Here, we report the confinement of multiple local phonons to a single ion site using this nonlinear quantum effect. By using phonon-number-resolving detection, we observe the dynamics of multiple phonons in an ion chain. In addition to simply confining local phonons, by turning the JC interaction on and off dynamically, we can confine a single local phonon to a single ion site and subsequently retrieve it out of the site. Our work establishes a key technological component for quantum simulation with multiple bosonic particles, which can simulate classically intractable problems.

INTRODUCTION

Trapped ions are a well-isolated and controllable system, providing an ideal platform for quantum information processing (QIP) and quantum simulation. The quantum state of an ion can be expressed by the internal and phonon degrees of freedom. In general, the internal states are used to encode qubits while phonons mediate interactions between the qubits. However, phonons in trapped ions are also a promising resource for QIP and quantum simulation themselves. It is possible to optically manipulate phonon states by driving motional sideband transitions. Also, due to their high Hilbert-space dimensions, trapped-ion vibrational modes offer large degrees of freedom for use in encoding qubits [1].

Phonons in trapped ions can be classified into collective-mode phonons [2,3] and local phonons [4]. When ions are tightly confined, the couplings between the ions are strong, resulting in collective oscillations. On the other hand, when the distance between the ions is large, the phonons are localized to each ion in a trapped-ion chain. These local phonons behave as if they were independent particles [5].1 Due to their particle-like characteristics and bosonic nature, local phonons can be applied to QIP [2,3] and quantum simulation of bosonic systems [4]. Additionally, local phonons play an important role in building two-dimensional (2D) trapped-ion systems for QIP and quantum simulation [15–17].

For these applications, an important challenge is scaling up the quantum system. A straightforward way is to simply increase the number of ions. However, by utilizing the phononic degree of freedom of trapped ions, we can make greater use of the high dimensional Hilbert space of the vibrational states in quantum simulation. Multiple local phonons in a trapped-ion chain can be used to solve intractable problems on a classical computer such as boson sampling [12,13]. Additionally, phonon propagation in a trapped-ion chain provides a platform to investigate the physics of quantum transport [18,20].

However, due to the difficulty in projective measurements of multiple phonons, there have been only a limited number of studies to date on multiphonon dynamics in trapped ion systems. Recently, phonon-number-resolving detection over multiple local-phonon modes has been demonstrated [10]. Using phonon-number-resolving detection, it is possible to measure the dynamics of multiple local phonons including the correlation between phonon modes.

In this paper, we demonstrate the confinement of multiple local phonons in a two-ion chain, where phonon blockade [9] is applied to control the propagation of local phonons. Debnath et al. demonstrated the blockade of a single local phonon in a three-ion chain and confinement of a phonon to a limited region of the chain [9], but the confinement of multiple local phonons has not yet been demonstrated. By driving the Jaynes–Cummings (JC) interactions, the internal states and the phonon states are coupled, resulting in an anharmonic ladder of JC eigenstates. This nonlinear quantum effect suppresses phonon hopping. To observe the phonon blockade of two local phonons, we implemented phonon-number-resolving detection [9]. Our work is an important step forward towards the realization of a large-scale quantum simulator with multiple phonons.

We also realize the confinement and retrieval of a single local phonon in a two-ion chain. Collective-mode phonons in trapped ions are considered to be well-defined and stable excitations, while local phonons, which are described as superpositions of collective-mode phonons, are unstable in principle, as is also the case for many other kinds of localized wave packets in classical or quantum physics. Therefore, confining local phonons to a limited spatial region and retrieving them at desired times
is non-trivial and requires experimental demonstration. The confinement and retrieval of a single local phonon demonstrated in this work may be extended to the preparation of highly non-classical phonon Fock states as well as the observation of such states, and to the control of the propagation of local phonons to realize time-dependent versatile couplings between local-phonon modes.

PHONON BLOCKADE

We first describe the principles of a phonon blockade. Here, $N$ ions with mass $m$ and charge $e$ form a linear chain in a harmonic potential. The confinement along the $z$ direction is relatively weak, resulting in large interion distances. Assuming $\hbar = 1$ and that the distance between the $i$th and $j$th ion is $d_{ij}$, the Hamiltonian of this system [Fig 1(a)] is described in terms of the local phonons as follows [4, 21, 22]:

$$H_0 = \sum_{i=1}^{N} (\omega_y - \omega_{y,i}) \hat{a}_i^\dagger \hat{a}_i + \sum_{i < j}^{N} \frac{\kappa_{ij}}{2} (\hat{a}_i \hat{a}_j^\dagger + \hat{a}_j \hat{a}_i^\dagger),$$

(1)

where $\kappa_{ij}$ and $\omega_{y,ij}$ are the hopping rate between the $i$th and $j$th ions and the site-dependent secular frequency shift of the $i$th ion, respectively. Here, $\omega_y$ is the secular frequency along the $y$ direction. Additionally, $\hat{a}_{i,y}$ and $\hat{a}_{i,y}^\dagger$ are the annihilation and creation operators, respectively, of the local phonon mode along the $y$ direction of the $i$th ion.

The phonon blockade is based on a quantum nonlinear effect induced by the JC interactions [9]. Illumination of an ion with a laser resonant with a red-sideband induces JC interactions. We assume that $g_{r,i}$ and $\Delta_{r,i}$ are the red-sideband Rabi frequency and the detuning from the resonance of the red-sideband transition for the $i$th ion, respectively. The Hamiltonian of this system is, then, described by the following Jaynes–Cummings–Hubbard (JCH) Hamiltonian.

$$H_{JCH} = H_0 + \sum_{i=1}^{N} \Delta_{r,i} \ket{\uparrow_i} \bra{\uparrow_i} + \sum_{i=1}^{N} \frac{g_{b,i}}{2} (\hat{a}_i \hat{\sigma}_i^- + \hat{a}_i^\dagger \hat{\sigma}_i^+).$$

(2)

Here, the internal states of an ion are represented as $|\uparrow_i\rangle$ and $|\downarrow_i\rangle$. $\hat{\sigma}_i^+ = |\uparrow_i\rangle \langle \downarrow_i|$ and $\hat{\sigma}_i^- = |\downarrow_i\rangle \langle \uparrow_i|$ are the raising and lowering operators for the $i$th ion respectively. In the JCH system, a polariton, a linear combination of internal atomic and phononic excitations, works as a conserved particle. As shown in Fig 1(b), the JC interaction results in an anharmonic ladder of JC eigenstates $|\pm, n\rangle$, where $n$ is the polaritonic excitation number and $+$ and $-$ represent higher and lower eigenenergy states, respectively. This energy splitting prevents local phonons from hopping to the illuminated site.

In the present experiment, we implemented a phonon blockade using the anti-JC interaction [23]. This can be realized by exciting the ions with lasers resonant with a blue-sideband transition. Therefore, the Hamiltonian is rewritten as follows.

$$H_{\text{anti-JCH}} = H_0 + \sum_{i=1}^{N} \Delta_{b,i} \ket{\downarrow_i} \bra{\downarrow_i} + \sum_{i=1}^{N} \frac{g_{b,i}}{2} (\hat{a}_i \hat{\sigma}_i^+ + \hat{a}_i^\dagger \hat{\sigma}_i^-),$$

(3)

where $g_{b,i}$ and $\Delta_{b,i}$ are the blue-sideband Rabi frequency and the detuning from the resonance of the blue-sideband transition for the $i$th ion. This Hamiltonian is essentially the same as Eq. (2) with the labeling of the internal states interchanged.
EXPERIMENTAL RESULTS

Confinement of a single local phonon

We first implement the blockade of a single local phonon in a two-ion chain as a preliminary experiment. Two $^{40}\text{Ca}^+$ ions, ‘ion1’ and ‘ion2’, are trapped in a linear Paul trap. The secular frequencies along the radial ($x$ and $y$) and axial ($z$) directions are $(\omega_x, \omega_y, \omega_z) = 2\pi \times (3.07, 2.87, 0.11)$ MHz. The distance between the ions is $\sim 24 \mu\text{m}$. We use the internal states $|S_{1/2}, m_j = -1/2\rangle = |\downarrow\rangle$ and $|D_{5/2}, m_j = -1/2\rangle \equiv |\uparrow\rangle$ to encode the spin states.

The experiment begins with the Doppler cooling of all motional modes and the ground-state cooling of radial motional modes. The narrow quadrupole transition, $S_{1/2} - D_{5/2}$, is used for the resolved sideband cooling. The local phonon mode along the $y$ direction is used. After sideband cooling, both ions are prepared as $|\psi\rangle_{\text{init}} = |\psi_{\text{ion1}}\rangle \otimes |\psi_{\text{ion2}}\rangle = |\uparrow, n_y = 1\rangle \otimes |\uparrow, n_y = 0\rangle \equiv |1, 0\rangle$. This state was generated by applying a carrier $\pi$ pulse ($\sim 0.8 \mu\text{s}$) to ion2 followed by a blue-sideband $\pi$ pulse ($\sim 16 \mu\text{s}$) applied to ion1. During the state preparation, a blockade beam detuned at the blue-sideband was applied to ion2. We then observe the local phonon population in each ion after waiting for a period equal to the phonon hopping time. Detection of a single local phonon is implemented by projecting the probability amplitude of $|\uparrow, n_y = 1\rangle$ onto $|\downarrow, n_y = 0\rangle$ by applying a blue-sideband $\pi$ pulse.

The experimental results of single-phonon hopping and the blockade are shown in Fig. 1(c) and Fig 1(d), respectively. The blue and red circles represent the probabilities for $|1, 0\rangle$ and $|0, 1\rangle$, respectively. Each data point is the average of 100 measurements. The solid lines are numerically calculated results based on Eq. (3). In the numerical calculation, we include the infidelities of the state preparation and mapping process. As seen from the results, hopping of the local phonon is significantly suppressed.

Confinement of two local phonons

We next perform an experiment for confining two local phonons to a single ion site. We first observed two-phonon hopping in a two-ion chain. As an initial state, two ions are prepared in $|\psi_{\text{init}}\rangle = |\psi_{\text{ion1}}\rangle \otimes |\psi_{\text{ion2}}\rangle = |\uparrow, n_y = 2\rangle \otimes |\uparrow, n_y = 0\rangle \equiv |2, 0\rangle$. To observe the multiple phonon dynamics, we use phonon-number-resolving detection [10]. The mapping process in this experiment is as follows. We apply a composite-pulse sequence at the blue-sideband transition to compensate the Rabi frequency difference between the transitions $|\downarrow, n_y = 0\rangle \leftrightarrow |\uparrow, n_y = 1\rangle$ and $|\downarrow, n_y = 1\rangle \leftrightarrow |\uparrow, n_y = 2\rangle$. Subsequently, a $\pi$ pulse at the carrier transition is applied. Then, the probability amplitude of $|\downarrow, n_y = 0\rangle$ is transferred to $|D_{5/2}, m_j = -1/2\rangle$, which has a lifetime of $\sim 1 \text{ s}$. By applying a carrier $\pi$ pulse followed by a blue-sideband $\pi$ pulse, every probability amplitude is mapped to the motional ground state. In this way, we eliminate the effect of phonon hopping during the detection. After the mapping process, state-dependent fluorescence detection is performed. If fluorescence is detected, the sequence is concluded at this point; otherwise, the probability amplitude of $|D_{5/2}, m_j = -1/2\rangle$ is mapped to that of $|\downarrow, n_y = 0\rangle$ while a further fluorescence detection concludes the sequence. We repeat this sequence until fluorescence is detected.

The observed two-phonon hopping dynamics are shown in Fig 2(a). The measured probabilities for $|2, 0\rangle$, $|1, 1\rangle$ and $|0, 2\rangle$ are shown as functions of the hopping time. The result of the blockade experiment is shown in Fig 2(b). The bottom graphs in Fig 2(a) and Fig 2(b) represent the numerically calculated results based on the Hamiltonian in Eq. (3), which includes the infidelities of the state preparation and mapping processes. As can be clearly seen, the hopping of the two local phonons is significantly suppressed.
Confinement and retrieval of a single phonon

By applying a time-dependent blockade beam to one of the ions, we demonstrate the confinement and retrieval of a single local phonon. The experimental sequence is schematically shown in Fig 3(b). We prepare two ions in $|1, 0\rangle$. The blockade beam is applied to ion2 for 190 $\mu$s. A waiting time of 230 $\mu$s ($\approx 1/2\kappa$) then follows. Subsequently, we apply the blockade beam to ion1 for another 190 $\mu$s and wait for 230 $\mu$s. Thus the dynamics of the local phonon is optically controlled. For comparison, we show free hopping results in Fig 3(a). In both figures, each data point is an average of 100 measurements and the solid lines are the numerical calculations.

DISCUSSION

A phonon blockade can be used to realize more complicated quantum simulations and quantum transport dynamics. For instance, it is possible to reconfigure the interactions between ions in a long trapped-ion chain by selectively illuminating the ions with blockade beams.

In addition, the implementation of a phonon blockade in a 2D Wigner crystal is an interesting future prospect. Coherent coupling between the motional states of separately trapped ions in a triangular lattice potential has recently been realized [16, 17]. By combining a phonon blockade with phonon propagation in a 2D trapped ion array [15–17], quantum transport in a 2D lattice graph with artificial defects can be simulated.

CONCLUSIONS

In conclusion, we have demonstrated the confinement of multiple local phonons. For detection of multiphonon dynamics, phonon-number-resolving detection has been implemented, and we have successfully observed the time evolution of the dynamics of multiple local phonons in a two-ion chain. Additionally, by applying a time-dependent blockade beam, the confinement and retrieval of a single phonon is realized.

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