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Strings of Ion Crystals in a Linear Trap for Quantum Information Processing *

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Strings of laser cooled $^{40}Ca^{+}$ crystals have been successfully confined in our home-built linear ion trap, and ready for quantum information processing. We find the cloud-crystal phase transition of the trapped ions to be strongly sensitive to the frequencies of the Doppler cooling lasers and to the trapping voltage. The quantum jump of a single ion has been observed by controlling the quadrupole transition of the ion by a weak laser with ultra-narrow bandwidth.

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To experimentally explore fundamental quantum mechanical problems, we need to produce a pure quantum system well isolated from the environment and under control. The system of laser cooled atomic ions confined in an electromagnetic potential is an ideal paradigm for this intention,[1] where the internal and motional degrees of freedom of the ions could be manipulated highly accurately and decoherence due to environment is nearly negligible.

Since the proposal by Cirac and Zoller,[2] cold trapped ions have drawn much attention for carrying out quantum information processing (QIP). The main idea is to encode qubits in the internal states of the ions, and interactions between the qubits could be made via the common quantized vibrational modes of the ions. To this end, exact and individual manipulation of the ions is required. So far, simple quantum algorithms have been accomplished[3] and entangling up to 14 ultracold ions has been demonstrated.[4] The scalable QIP with the trapped ions could be hopefully carried out by moving the ions from one zone to another in a multi-trap device[5] or by entangling spatially separate ions by parity projection of the emitted photons.[6] Recently, great efforts have been taken to quantum simulation with the trapped ion.[7–9] Further reading is available in some review articles.[10–12]

In this Letter, we report our latest experimental implementation on cold $^{40}Ca^{+}$ ions confined in our home-built linear trap. We investigate the cloud-crystal phase transition of the ions from the fluorescence spectrum and demonstrated different numbers of ions in spatially crystalline orders. We also observe the quantum jump of a single ion, which is the prerequisite for manipulation and readout of the $^{40}Ca^{+}$ qubits. This implies that our setup is ready for QIP.

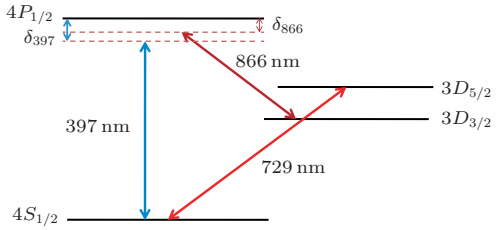

Fig. 1. Level scheme of $^{40}Ca^{+}$ ion (not scaled) with the lasers employed in our experiment, where δ_{397} and δ_{866} are detunings regarding the cooling and the repumping lasers, respectively.

Our interests in trapping $^{40}Ca^{+}$ ions are motivated by our experience in studying $^{40}Ca^{+}$ ions and also by the fact that the cooling of $^{40}Ca^{+}$ ions could be carried out by commercially available lasers (see Fig. 1). The $^{40}Ca^{+}$ ions are trapped in a home-built linear Paul trap,[13] where four blade-like electrodes with diagonally opposite blades distant by 1.6 mm are used for the radio-frequency (rf) radial confinement. A home-made rf drive at 19.6 MHz is applied on the blades with voltage V_{p-p} in the range of 500–2000 V, resulting in the radial secular frequency of 700–1500 kHz. Axial confinement is achieved by dc voltage on two tip electrodes spaced by 5 mm, where the dc positive voltage in the range of 15–80 V corresponds to the axial secular frequency 90–470 kHz. Two compensation electrodes are used to balance the external stray field and reduce rf heating. The experimental setup is plotted in Fig. 2, where the trap is fixed in the center of a vacuum chamber with the vacuum remained by a 40 L/s ion pump and a titanium sublimation pump. A pressure lower than 10^{-9} mbar in the chamber can

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be inferred from the measured current smaller than 0.1 μA through the ion pump.

The trapped $^{40}Ca^{+}$ ions are Doppler cooled using electric dipole transition between the $4^2S_{1/2}$ ground state and the $4^2P_{1/2}$ excited state. This transition is driven using the light with a wavelength near 397 nm generated by a commercial external cavity diode laser. As the spontaneous emission occurs with 6% probability down to the metastable level $3^2D_{3/2}$, we have to repump the population at $3^2D_{3/2}$ back to $4^2P_{1/2}$ by the 866 nm laser which is a home-made external cavity diode laser. In addition, an ultra-stable Ti:Sapphire laser for 729 nm is employed for the quantum jump from $3^2D_{5/2}$ to $4^2S_{1/2}$. Three laser beams are overlapped and focused at the center of the trap, where the power and the beam waist are 30 μW and 50 μm respectively for 397 nm laser, 200 μW and 100 μm respectively for 866 nm and 10 μW and 100 μm respectively for 729 nm laser.

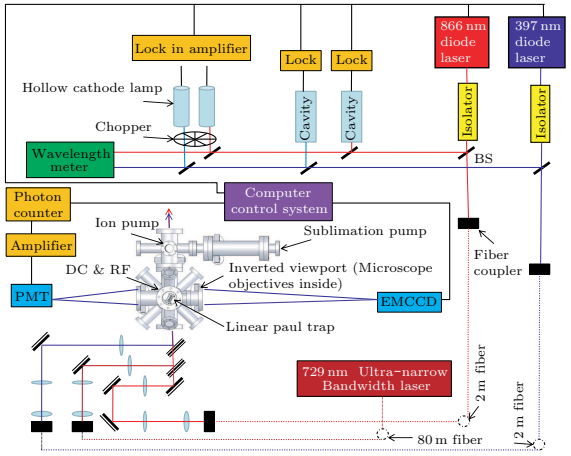

Fig. 2. Schematic of our experimental setup, where the details are explained in the text.

The detection is made by both photon counting and imaging. The photon counting system consists of a set of microscope objective with enlargement of 7, a photon multiplier tube plus a fast preamplifier and a photon counter. The fluorescence is collected by the microscope objective, and then focused to a 1.2-mm-diameter pinhole with a filter at 397 nm. The data are recorded by the PMT and finally stored by a computer. The imaging system includes a set of microscope objective with 15 times magnification and an electron-multiplying CCD (EMCCD). The 397 nm photons from the trapped ions by spontaneous emission yield the image of the ions on the EMCCD.

At the beginning of the experiment, the 397 nm laser is red detuned by about 1 GHz (i.e., $\delta_{397} = -1$ GHz) and the 866 nm laser is set on resonance (i.e., $\delta_{866} = 0$). Then the calcium oven is heated to a temperature slightly higher than the melting point of the calcium atoms in the ultra-high vacuum. After the heating for 1 min, we turn on the electron gun for 30 s. The calcium ions are produced in the trap center by the electron bombardment on the atomic beam from the calcium oven. When the loading process is finished, we scan the 397 nm laser repeatedly from red detuning to near resonance, and the success of trapping could be evidenced by both PMT and EMCCD. Under appropriate trapping condition, the ions would stay stably as a cloud, as shown in Fig. 3(a). By measuring the ion charge density, we can identify the number of ions in the cloud. For the image in Fig. 3(a), the number of ions is about 400. Meanwhile, the ion cloud is monitored by PMT. For colder trapped ions, we may collect more fluorescence. Since the radiation by the 397 nm laser makes not only excitation but also cooling, more photons will be collected with the scanning of the red-detuned laser. Thus the left part of the spectrum in Fig. 3(b) corresponds to the ions getting colder. However, the right part of the spectrum is due to blue detuning of the scanning laser, which yields Doppler heating. As a result, there is a sharp drop in the spectrum for the positive detuning, implying less and less photons collected with the blue-detuning scanning.

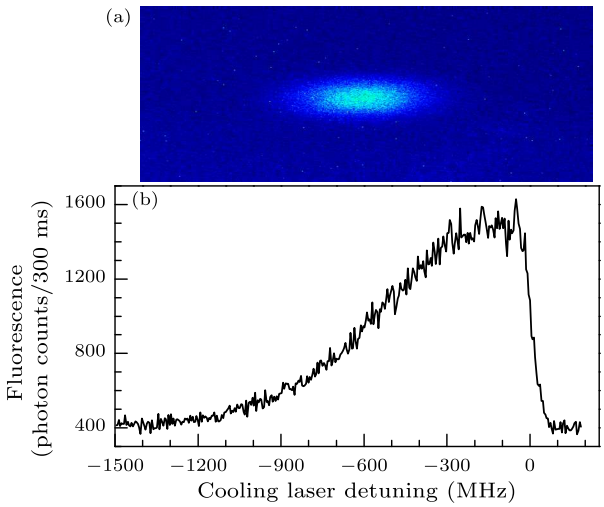

Fig. 3. A cloud of ions trapped stably after loading, with (a) the image of the ion cloud by EMCCD and (b) the fluorescence spectrum of the ion cloud by PMT.

The measurement of the fluorescence with respect to the detuning of the laser gives useful information about the dynamics of the trapped ions. Due to the Coulomb repulsion and the rf heating, the trapped ions collide strongly with each other in the trap. As a result, only if the cooling rate is much larger than the heating rate, will the crystallization of the ions occur. To track the crystalline formation of the ions, we reduce the rf and dc voltage to a special value so that the ions oscillate in the Mathieu stability regime. Then

we monitor the PMT by scanning the cooling laser repeatedly. Figure 4 shows the fluorescence spectrum as a function of the detuning δ_{397} in such a scanning process, where the phase transition of the trapped ions from the cloud to the crystal experiences a dip, implying an intense competition between the rf heating effect and the laser cooling force.[14] It is also the starting point of the crystallization of the ions. The phase transition is very sensitive to the variation of the rf field and the radiated lasers. The increase of the rf voltage could make the crystals fragile, and slightly changing δ_{866} could also melt the crystals.

With a different loading process, we have observed spatially resolved ion strings involving different numbers of ions, as shown in Fig. 5, where we set the exposure time to be 1 s, the axial secular frequency $\omega_z = 2\pi \times 379$ kHz and radial secular frequency $\omega_r = 2\pi \times 760$ kHz. The typical spacing between two neighboring ions is about 10 μm. The trapped ions in crystalline order is essential for us to make reliable and efficient manipulation on qubits.

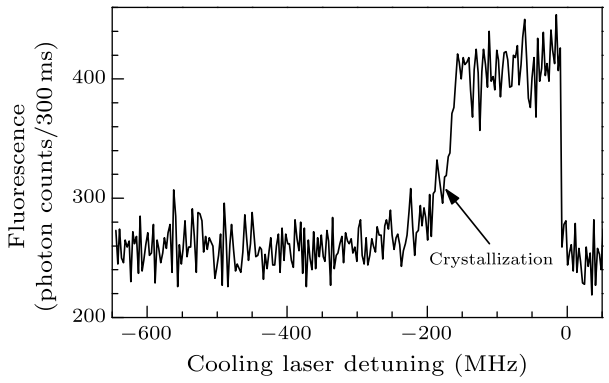

Fig. 4. The phase transition of two $^{40}Ca^{+}$ ions from cloud to crystal, where the arrow points to the dip, the starting point of the crystalline formation. The radial secular frequency is $2\pi \times 750$ kHz and the axial secular frequency is $2\pi \times 370$ kHz.

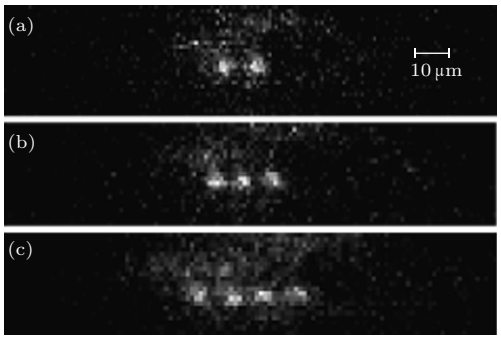

Fig. 5. The images of strings of ion crystals with (a) two ions, (b) three ions and (c) four ions.

We have also checked the quantum jump in the case of a single trapped ion.[15,16] If the level $4^2S_{1/2}$ is populated, constant fluorescence would be obtained under the radiation of 397 nm and 866 nm lasers. However, once the population is transferred to a metastable level $3^2D_{5/2}$ by the 729 nm laser, the fluorescence will disappear until dissipation from $3^2D_{5/2}$ to $4^2S_{1/2}$ occurs. The sudden drop of the fluorescence is called the quantum jump because it happens in a single ion and the time period without fluorescence is called the dark period. As shown in Fig. 6, we have clearly observed the quantum jump and the dark periods.

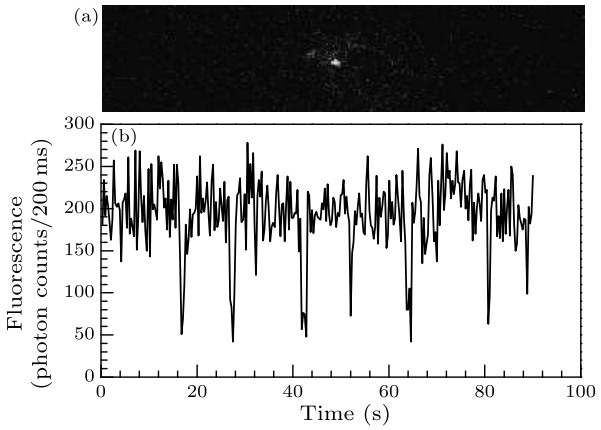

Fig. 6. Quantum jump of a single ion. (a) The single ion image on the EMCCD. (b) Spectrum of the quantum jump by PMT.

To perform QIP, we need to prepare the initial states of the qubits, coherently manipulate the qubits, and finally read out the information from the qubits. To accomplish these operations exactly and coherently, we require the ions to be cooled to ground vibrational states by sideband cooling. For $^{40}Ca^{+}$ ions, the sideband cooling could be carried out using ultranarrow band 729 nm laser with red-detuning on the quadrupole transition between $3^2D_{5/2}$ and $4^2S_{1/2}$. If the sideband cooling has succeeded, to carry out gate operations, we may encode qubits in the levels $3^2D_{5/2}$ and $4^2S_{1/2}$. As a result, besides the use in sideband cooling, the 729 nm laser also plays an important role in the initial state preparation, the gating operation and the readout. This also implies that our operation for quantum jump is the prerequisite for our next work for QIP.

In summary, we have successfully confined and laser-cooled $^{40}Ca^{+}$ ions in our home-built linear trap. By elaborately adjusting the trapping potential and the lasers, we have demonstrated strings of spatially resolved ion crystals, which implies our capability of controlling trapped ion qubits. Further improvement of the laser frequency stability is necessary, which will make it possible to investigate the phase transition more clearly and keep the crystals more stably. Sideband cooling of the ions is on the way, and QIP with

the trapped ions will soon be available.

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