Controlling Fast Transport of Cold Trapped Ions


QUANTUM, Institut für Physik, Universität Mainz, Staudingerweg 7, 55128 Mainz, Germany

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We realize fast transport of ions in a segmented microstructured Paul trap. The ion is shuttled over a distance of more than $10^4$ times its ground state wave function size during only five motional cycles of the trap ($280 \mu m$ in $3.6 \mu s$). Starting from a ground-state-cooled ion, we find an optimized transport such that the energy increase is as low as $0.10 \pm 0.01$ motional quanta. In addition, we demonstrate that quantum information stored in a spin-motion entangled state is preserved throughout the transport. Shuttling operations are concatenated, as a proof-of-principle for the shuttling-based architecture to scalable ion trap quantum computing.

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The experiments are carried out in a microstructured segmented Paul trap [14], where the trapping voltage applied to each electrode segment is controlled by an...
FPGA-based arbitrary waveform generator that allows high resolution for both timing and voltage, while having low noise ($\leq 10\ n\text{V}/\sqrt{\text{Hz}}$ at the trap frequency). Further noise reduction at high frequencies is done with a II-type filter having a cutoff frequency of 300 kHz. The axial trap frequency is $\nu_{\text{ax}} = \omega_{\text{ax}}/2\pi = 1.41\ MHz$, while the radial trap frequencies are $\sim 3\ MHz$. The transport is carried out by varying the voltages on the segments, such that the minimum of the trapping potential is moved toward the final location in time steps of 400 ns. In order to minimize parametric excitation, the confinement strength of the trap should remain as close as possible to its original value during transport. To assure this, the voltages required for creating a trap minimum with predefined frequency at a given location are calculated a priori. This relation is established using numerically obtained data for the electrostatic trap potentials [15] and has been experimentally verified [16]. The ion used for the experiments is $^{40}\text{Ca}^{+}$, where an external magnetic field splits the $S_{1/2}$ ground state into two levels, $m_J = \pm 1/2$, henceforth referred to as $|\downarrow\rangle$ and $|\uparrow\rangle$. Qubit rotations between these levels are mediated by stimulated Raman transitions [17,18]. Each experimental run is started by Doppler cooling and followed by optical pumping, leaving the ion in the $|\downarrow\rangle$ state. Resolved sideband cooling is then used to prepare the ion close to the motional ground state at a mean thermal phonon number of about $\bar{n}_{\text{th}} = 0.1$ phonons, to which the motional excitation is then compared. Following this, a transport operation is performed. For determining the motional state, stimulated Raman transitions between $|\downarrow\rangle$ and $|\uparrow\rangle$ are driven by a pair of off-resonant beams propagating at 90° with respect to each other. The effective wave vector of the beams is aligned along the trap axis, providing a coupling to the axial mode of vibration, characterized by a Lamb-Dicke factor of $\eta = 0.23$. Finally, spin readout is performed by a shelving pulse followed by the detection of state-dependent fluorescence [17].

For evaluating the performance of the transport, it is important to have a reliable and efficient method for measuring the amount of motional excitation of the ion. While the dynamics of the ion shuttling is of classical nature, the precision which is required calls for energy measurements schemes which work quantum mechanically, i.e., down to the single-phonon regime. Doppler recooling [19] and ion loss rates have previously been used to measure extremely large energy transfers [20]. Rabi oscillations on the motional sidebands of the Raman transition [see Fig. 2(a)] provide an accurate but time-consuming tool for reconstruction of the motional state [21]. The measurement principle is based on the dependence of the Rabi frequency on the phonon number, which manifests itself in the Rabi oscillation signal:

$$P_{\uparrow,\Delta n}(\theta) = \frac{1}{2} \sum_{n=0}^{n_{\text{max}}} p_n [1 + \cos(M_{n,\Delta n} \theta)],$$

where $P_{\uparrow,\Delta n}(\theta)$ indicates the measured probability for finding the ion in the $|\uparrow\rangle$ level after driving the stimulated Raman transition, $|\uparrow, n\rangle \rightarrow |\downarrow, n + \Delta n\rangle$, with a pulse area of $\theta$. The Rabi frequency is altered by the matrix element $M_{n,\Delta n}$ [18]. The phonon probability distribution $p_n$ is given by a convolution between a thermal and a coherent phonon distribution:

$$p_n = \sum_{m=-n}^{N} \frac{\bar{n}_{\text{th}}^m}{(\bar{n}_{\text{th}} + 1)^{n+1}} \frac{\bar{n}_{\text{a}}^{(n-m)}}{(n-m)!},$$

where $\bar{n}_{\text{th}}$ is the thermal mean phonon number and $\bar{n}_{\text{a}} = |\alpha|^2$, the mean phonon number arising from the coherent displacement, characterized by an amplitude $\alpha$, allowing for a distinction between the two distributions. The mean phonon numbers are extracted by performing a simultaneous Bayesian analysis of data sets pertaining to different transitions, $\Delta n$, for a given shuttling operation. Imperfect readout and preparation, as well as dephasing of the Rabi oscillations from other decoherence sources, are taken into account. Thus, estimations and valid confidence intervals for the mean phonon numbers, $\bar{n}_{\text{th}}$ and $\bar{n}_{\text{a}}$, are obtained for each data set. For low excitation energies, probing is done on the transitions $\Delta n = -1, 0, 1$.

FIG. 2 (color online). Determination of the motional excitation. (a) Relevant levels and transitions in the $^{40}\text{Ca}^{+}$ system. For the determination of the phonon number, we use two methods based on the excitation of sidebands. (b) Phonon number as a function of the pseudoenergy quantity (see text), indicating the bijective nature for $\bar{n}_{\text{a}} \approx 50$. Rabi oscillations for the carrier (black), first blue (blue), first red (red), and second red (dark red) sideband, (c) for the case of $\bar{n}_{\text{a}} = 0.10 \pm 0.01$, and (d) $\bar{n}_{\text{a}} = 20 \pm 0.13$. 

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The indices refer to the blue ($\Delta n = +1$), red ($\Delta n = -1$), and second red ($\Delta n = -2$) motional sidebands, probed at the time it would take the carrier to reach the indicated pulse area. For phonon numbers below $\tilde{n}_a \approx 50$, this measure is positive and monotonically increases with the phonon number [see Fig. 2(b)] and is moreover robust against small fluctuations of the transition frequencies, laser beam intensities and readout imperfections. For mean phonon numbers $> 50$, the pseudoenergy may still be used, but one must take care of the conversion ambiguity, visible in Fig. 2(b).

We use the pseudoenergy to investigate how the motional energy of the ion depends on a dwell time, $\tau_d$, between two fast transport operations, i.e., the pair-neutral scheme. The ion starts out in segment A [see Fig. 1(a)] and is then transported to segment B, where it remains for a time period that can be altered in steps of 20 ns (on top of the 400 ns update time), before being transported back to segment A where the readout takes place. The result is presented in Fig. 3(a). We observe a periodic dependence on the dwell time, with minima in intervals of $1/\nu_{ax}$. A few points are evaluated more accurately using the sideband Rabi oscillation method, and for the dips we find minimum excitations of $\tilde{n}_a = 0.10 \pm 0.01$ phonons. When the dwell time, instead, is such that the momentum transfer from the first and the second transport add up, we find a maximum, where fits to the Rabi oscillations are consistent with a coherent state phonon distribution with up to $\tilde{n}_a \approx 100$ phonons. As expected, the energy transfer from the first shuttle can be coherently removed by the transport back, with a periodic dependence on the dwell time.

For the energy self-neutral shuttling, a sharp kick is used to stop the motion. This is realized by applying a voltage pulse on a nearby electrode segment, being active for only one update sample of the waveform generator (400 ns). The kick delay time, $\tau_k$, between the last voltage update of the transport and the stopping momentum kick is scanned. This effectively changes at which phase in the motional period the force is applied, thus either adding or removing motional energy. The transport back to segment A is performed adiabatically, such that this part contributes only negligibly to the final excitation. The result is presented in Fig. 3(b), where both a positive and a negative voltage kick amplitude is shown, displaying a shift of half a cycle with respect to each other. The amplitude of the voltage kick is calibrated by minimizing the energy transfer at the kick delay time corresponding to the minimum. The self-neutral transports display an excitation as low as the pair-neutral ones but allow even faster shuttles. The shortest duration for which transport with negligible excitation was achieved was $3.6 \mu s$, which corresponds to about 5 oscillation cycles, plus a delay time of $\tau_k = 220 \text{ ns}$.

For both types of transports, the results were obtained using ramps where the spatial location of the ion varies in a sin$^2$ shaped manner with respect to time. Other ramp shapes, such as a linear one, yield different results but are also able to realize energy-neutral transport, as considered previously [22,23]. We also applied both shuttling protocols to two-ion crystals, obtaining similarly low energy increases on both the common and stretch modes of oscillation. The results show that we obtain a high degree of control over the dynamics of trapped atomic particles. The placement accuracy in phase space is given by the minimum excitation of 0.1 phonons compared to the phase space volume occupied by the shuttling trajectory in units $\hbar$. From this, we attain a relative accuracy on the order of $10^{-8}$.

So far, we have shown that after a fast shuttle, the motional ground state ($n = 0$) can be recovered. This control is now extended to spin-motion entangled states:
We investigate how quantum information can be stored, and transported, in a superposition of Fock states. For this, we perform a spin echo experiment using pulses on the blue sideband Raman transition, where a pair-neutral transport is carried out in the second branch. Starting with the ion in state $|\uparrow, n = 0\rangle$, a $\pi/2$ pulse on the blue sideband will put the ion into the state $|\uparrow, n = 0\rangle + e^{i\phi} |\downarrow, n = 1\rangle$, a spin-motion entangled state with phase $\phi = 0$. After the shuttling, a phase shift of this state will arise from changes to the energy levels of both the spin and the motional part of the wave function. If one can assure that the spin level splitting remains constant, any measured phase shift will reveal changes to the motional energy level spacing, making it a versatile and precise probe of the time-dependent trapping potential. In Fig. 4(a) and 4(b), spin echo contrast curves are displayed, where the phase of the concluding $\pi/2$ pulse is varied. The data in Fig. 4(a) is obtained using the carrier transition with and without transport. After a magnetic field gradient compensation has been performed [24], no phase shift between the two data sets is obtained, proving that the Zeeman splitting between the spin energy levels remains constant during the transport. The data in Fig. 4(b) is obtained using the blue sideband transition, and the phase shift visible in the transported case is thus acquired solely from the motional energy difference of the spin-motion entangled state.

Upon using the spin-motion entangled state as a sensitive probe for the phonon energy level splitting, we found that the trap frequency varied slightly with the distance between the segments, due to technical imperfections. This resulted in a spatial modulation of the trap frequency by at most about 80 kHz for an ion position right between the two segments, and near zero directly above the segment centers. A set of position-dependent correction factors can be readily obtained by scanning the dwell time at various distances and for varying voltages, such that the phase shift is zeroed at each location. After this procedure, the probing is repeated and we find that the trap frequency deviations are reduced by two orders of magnitude, down to the measurement precision of 390 Hz, using a dwell time of 100 $\mu$s. This corresponds to less than one per thousand of the trap frequency, as shown in Fig. 4(c). It is interesting to consider that the quantum information stored in a coherent superposition of two Fock states, even though being displaced by more than 100 phonons during the transport, can be fully retrieved.

We have demonstrated fast shuttling operations with small residual motional excitation, such that the ion ends the transport near the motional ground state. We also showed that qubit information is preserved through the shuttling by transporting a spin-motion entangled state with negligible loss of coherence. As a next step, we intend to perform fast-splitting operations of multi-ion crystals. Our long-term goal is to extend the transport scheme to parallel operations on multiple segments and combine it with laser-driven quantum logic gates.

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Note added.—Recently, we became aware of similar results by another group [25].

*Corresponding author: poschin@uni-mainz.de; www.quantenbit.de