# High fidelity quantum entanglement and spin-spin dynamics using multiple phonon modes of several trapped ions

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**Abstract:** We demonstrate quantum entanglement and global spin dynamics between a few trapped ions, using lasers that couple to all modes of transverse motion in a way that could be scaled to large numbers of spins.

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## 1. Introduction

During the last decade, trapped ion systems have fulfilled all of the basic requirements for practical quantum information processing, and the central task is now to scale this system to larger numbers of qubits. Indeed, there are particular tasks in quantum simulation that could surpass the performance of classical computations with with just a few dozen qubits. There are several approaches to scaling up the number of trapped ion qubits, such as entangling small numbers of ions based on a single collective mode of their Columb-coupled motion and shuttling the ions through complex trap structures [1] or using a probabilistic ion-photon interface [2]. Recently it was proposed that large stationary crystals of ions might be entangled by using all of their transverse modes of collective motion simultaneously [3]. This proposal is promising, because it does not require shuttling individual ions or new trap technologies for scaling up to dozens to hundreds of ions.

In the linear Paul trap, the anisotropy between the center-of-mass transverse trap frequency $\omega_t$ and axial trap frequency $\omega_a$ must be kept larger than a stability threshold that is nearly proportional to the number of ions. Given a maximum value of $\omega_t$ from voltage and geometry limits, $\omega_a$ must therefore be reduced significantly as the number of ions is increased. All previous quantum gate operations with ion qubits have relied upon the axial normal modes, so the number of ions in one trap was quite limited. On the other hand, $\omega_t$ can be kept at high frequency regardless of number of ions. These modes can also be densely packed, and this allows the operation of quantum entangling operations by driving multiple motional modes simultaneously.

We report the experimental realization of high fidelity quantum gates by driving multiple transverse modes and the experimental control of the spin-spin interaction through the laser detunings from the transverse motional modes. We also investigate this coupling to simulation interesting spin Hamiltonians such as a long-range Ising spin models with which can be written by $H = \sum_{i,j} J_{ij}\sigma_i^x\sigma_j^x$, where $J_{ij}$ is the interaction between $i$-th and $j$-th spins, $\sigma_i^x$ is the $i$-th spin along x axis.

## 2. Experiments

In the experiment, the ground two hyperfine states of $^{171}\mathrm{Yb}^+$, $|0\rangle = |F=0, m=0\rangle$ and $|1\rangle = |F=0, m=0\rangle$ separated by $\omega_{HF}$ = $(2\pi)$12.6 GHz, are used as the qubit or quantum spin. The qubits are all initialized in the state $|0\rangle$ after Doppler and sideband cooling, and at the end of each experiment we detect the final state through standard state-dependent fluorescence techniques. We repeat the same experiment 500-1000 times and average the results. For the quantum operations, we used Raman lasers of which frequency differences are around $\omega_{HF}$. The net momentum transfer from the two laser beams $\hbar\Delta k$ is set perpendicular to the ion string axis in order to couple to the transverse modes.

For the quantum gate of multiple motional modes, we set $\omega_a$ = $(2\pi)$ 0.6 MHz and $\omega_t$ = $(2\pi)$ 4.0 MHz for two ions. The difference of the center-of-mass mode $\omega_t$ and the "zig-zag" mode $\omega_{zz}$ is only $(2\pi)$ 53.3 kHz. The gate is performed by applying two Raman lasers near the blue and red sidebands with difference frequencies $\omega_{HF} \pm (\omega_t + \delta)$ [4]. Here, the detuning $\delta$ bisects the two modes, $\delta = (\omega_t - \omega_{zz})/2$ = $(2\pi)$ 26.6 kHz, as shown in Fig.1(a). When the sideband transition strength is set to $2\sqrt{2}\eta\Omega = \delta$ by adjusting the laser power, the entangled state $|00\rangle + |11\rangle$ is created at $T = 2\pi/\delta = 37.5\mu s$ [4]. Fig. 1(b) shows 15 successive operations of this gate, with a decrease in contrast of 71%, implying a single-gate operation fidelity of approximately 98%.

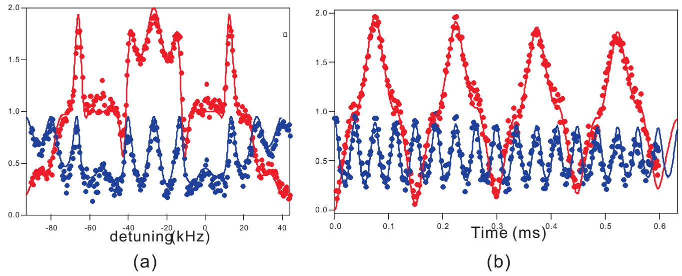


Fig. 1. The average brightness of PMT signal (red) and the parity signal (blue) depending on (a) the bichromatic detuning $\delta$ at 75 $\mu s$ duration of the lasers and (b) time at $\delta$ = $(2\pi)$ 26.6 kHz. Here dots are from experiments and solid curves are from theory including decoherences of simple exponential decay. In (a), the detuning axis is offset so that the center-of-mass mode is at 0 and the zigzag mode is at -53.2 kHz.

For the study of spin-spin dynamics, we used $\omega_a$ = $(2\pi)$ 1.4 MHz, $\omega_t$ = $(2\pi)$ 4.0 MHz with three ions. When the detuning $\delta >> \eta\Omega$, we can generate nearly pure spin-spin interactions with vanishing phonon populations. Given the motional mode spacings, laser detunings and powers, the Ising spin-spin coupling matrix $J_{ij}$ is given by

$$J_{ij} = \Omega_i \Omega_j \frac{\hbar}{2m} \sum_k \frac{b_i^k b_j^k}{\omega_k^2 - \delta^2}, \tag{1}$$

where $m$ is the mass of a single ion, $\Omega_i$ is the Rabi frequency of $i$-th ion, $b_i^k$ is the normal mode matrix describing the $i$-th ion's contribution to the $k$-th motionala mode, $\omega_k$ is the $k$-th mode frequency, and $\delta$ is the bichromatic laser detuning from the resonant spin transition as above. In the experiment, we observe the evolution of the spin populations from the interactions and invert the data to extract the spin-spin couplings $J_{ij}$. Fig. 2 shows the comparison of the experimental results with the above equation, showing good agreement with no free fit parameters.

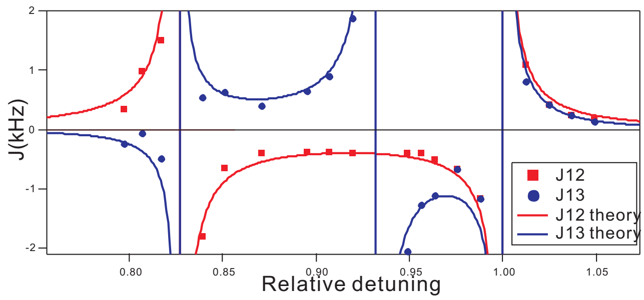


Fig. 2. $J_{12}$(red) and $J_{13}$ (blue) depending on bichromatic laser detuning at the given phonon mode spacings. Dots are from the experiments and the solid curve is theory from Eq. (1). The detuning axis is scaled to the center-of-mass mode frequency $\omega_t$, and the vertical lines indicate the positions of the three normal modes of transverse motiion. We note that in regions where $J_{1,3} > 0$, the Ising Hamiltonian is frustrated.

## 3. Conclusions and outlook

These experiments represent the first use of transverse motional modes of trapped ions for quantum entanglement studies, and such an approach looks promising for the scaling to large numbers of ions. In particular, this work could be applied in the near future to the simulation of more complex spin-spin models where classical simulation is inefficient.

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## References

1. D. Kielpinski, C. Monroe, and D.J. Wineland, *Nature* **417**, 709 (2002).
2. D. L. Moehring, M. J. Madsen, K. C. Younge, R. N. Kohn, Jr., P. Maunz, L.-M. Duan, C. Monroe, and B. Blinov, J. Opt. Soc. Am. B **24**, 300 (2007).
3. G.-D. Lin, S.-L. Zhu, R. Islam, K. Kim, M.-S. Chang, S. Korenblit, C. Monroe, and L.-M. Duan, arXiv 0901.0579 (2009).
4. A. Sørensen and K. Mølmer, Phys. Rev. Lett. **82**, 1971 (1999).
5. D. Porras and J. I. Cirac, Phys. Rev. Lett. **92**, 207901 (2004); X.-L. Deng, D. Porras, and J. I. Cirac, Phys. Rev. A **72**, 063407 (2005).
6. A. Friedenauer, H. Schmitz, J. T. Glueckert, D. Porras and T. Schaetz, *Nature Physics* **4**, 757 (2008).