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Realization a phononic network with collective modes in trapped ion system

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A network of bosons evolving among different modes while passing through beam splitters and phase shifters has been applied to demonstrate quantum computational advantage. Such networks have mostly been implemented in optical systems using photons. However, technical bottlenecks exist in photon systems. In particular, photon loss and non-deterministic generation and inefficient detection of photonic states hinder their further scalability and the demonstration of quantum advantage. It thus becomes desirable to explore new experimental platforms.

Quantized excitations of vibrational modes (phonons) of trapped ions are a promising candidate to realize such bosonic networks. Here, we demonstrate a minimal-loss programmable phononic network in which any phononic state can be deterministically prepared and detected[1]. We realize networks with up to four collective vibrational modes, which can be extended to reveal quantum advantage. This network has the capability that couple the ions with vibration modes to prepare, interfere, and measure phonons distributed in different modes, which achieves the ability to act as a boson sampling platform.

We experimentally demonstrate that phonons can be deterministically prepared and detected and that the number of phonons is nearly conserved while propagating in the network. By programmable operations throughout the boson sampling experiment, our system has demonstrated the ability to implement bosonic algorithms with high fidelity. We benchmark the performance of the network for an exemplary tomography algorithm using arbitrary multi-mode states with fixed total phonon number. We obtain high reconstruction fidelities for both single- and two-phonon states. Our experiment demonstrates a clear pathway to scale up a phononic network for quantum information processing beyond the limitations of classical and photonic systems.

Furthermore, we explore the possibility of realizing fault-tolerant quantum computation with error mitigation scheme, which can be realized with current system scale and fidelity. Based on quantum channel purification method, we are able to suppress all kinds of incoherent noise in unitary phonon operations. Our research will promote the development of quantum error mitigation in the spin-phonon hybrid system in ion trap, and provide a reference for the implementation of large-scale bosonic algorithms.

[1] Chen, W., Lu, Y., Zhang, S., Zhang, K., Huang, G., Qiao, M., … & Kim, K. (2023). Scalable and programmable phononic network with trapped ions. Nature Physics, 19(6), 877-883.

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