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Exponential inefficiency in quantum simulation of bosons, and its cure

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Hamiltonian quantum simulation of bosons on digital quantum computers requires truncating the Hilbert space to finite dimensions. We highlight that naive schemes, such as Fock basis truncation, can result in an exponentially large number of Pauli strings in the truncated Hamiltonian, with regard to the number of qubits Q assigned to each boson. Even a small departure from the diagonal form can lead to a significant complexity in the Pauli string expansion. This, in turn, can lead to an exponential increase in the complexity of the quantum circuit. Essentially the same problem can appear in different forms, such as a necessity of building oracles in certain algorithms that require exponentially large resources on classical computers. However, this problem can easily be avoided using the universal framework advocated by Halimeh et al. that combines truncations in coordinate and momentum bases, with the two bases connected through a quantum Fourier transform. For Yang-Mills theory and QCD, this problem can be addressed by utilizing the orbifold lattice Hamiltonian. In contrast, we do not find a suitable resolution when using the Kogut-Susskind Hamiltonian because of the lack of a quantum Fourier transform. In the continuum limit of the lattice Hamiltonian, the value of Q must be large, and this difference can lead to a parametrically large advantage for the orbifold lattice Hamiltonian. Specifically, the difference is a logarithm versus an impractically large power concerning the ultraviolet cutoff scale. We also point out a potential exponential increase in the resource requirement for formulations based on gauge-invariant Hilbert space, which can eliminate any quantum advantage.

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