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Studying the Entanglement of Multiqubit States with Quantum Technologies

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N. A. Susulovska, Kh. P. Gnatenko

Professor Ivan Vakarchuk Department for Theoretical Physics,
Ivan Franko National University of Lviv, Lviv 79005, Ukraine

The utilization of entangled multiqubit resource states is a cornerstone of practical quantum computing allowing for the development of innovative quantum algorithms, which facilitate computational advantage over classical approaches. On the other hand, thanks to the recent advancements in quantum technologies, quantum processors can be exploited to model systems of many spins and investigate the properties of their states with quantum programming methods.
Presently, we consider multiqubit states with different types of interaction and study their entanglement both analytically and with the help of quantum computations. The focus is on establishing efficient representations for the classes of quantum states of interest in terms of complex mathematical structures such as graphs, hypergraphs and further determining the relationships between physical properties of such states and geometric properties of the proposed representations. Namely, we examine graph states generated by the action of controlled phase-shift operators on an arbitrary separable state of the multipartite system, which allows us to study bipartite interactions [1], [2]. Subsequently, we consider quantum hypergraph states, which constitute a generalization of graph states permitting the introduction of multipartite interactions via the utilization of hyperedges [3]. In this context, 3-uniform hypergraph states prepared with the help of RZZY gates are investigated in detail. In both cases quantum states represented by graphs or hypergraphs of different connectivity are considered. In order to quantify the entanglement of multiqubit states under investigation we resort to the definition of the geometric measure of entanglement and leverage its relation to the mean spin, a quantity easily measurable on a quantum computer [4]. Analytical expressions for the geometric measure of entanglement of an arbitrary qubit with the remaining system in graph and hypergraph states are derived, which allows us to analyze its dependency on the state parameters. In specific cases the relationship between the geometric measure of entanglement of a qubit and its corresponding vertex degree is obtained. Additionally, we prepare graph and hypergraph states on gated-based quantum devices, namely both IBM's quantum simulator Qiskit Aer and real quantum hardware [5], and detect the associated geometric measure of entanglement based on mean spin measurements. Corresponding quantum computations support or theoretical findings and showcase the capabilities of current quantum computers in the studies of physical systems.

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Primary authors: Ms SUSULOVSKA, Nataliia (Professor Ivan Vakarchuk Department for Theoretical Physics, Ivan Franko National University of Lviv); Prof. GNATENKO, Khrystyna (Professor Ivan Vakarchuk Department for Theoretical Physics, Ivan Franko National University of Lviv)

Presenter: Ms SUSULOVSKA, Nataliia (Professor Ivan Vakarchuk Department for Theoretical Physics, Ivan Franko National University of Lviv)

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