Quantum computing simulation of Quantum Spin Liquids

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Brief Description of the Challenge:

Quantum Spin liquids (QSL) are a special quantum state of matter which has been theoretically formulated but not yet proven to be possible. If this state is viable, it will open the way to the development of new materials showing extraordinary properties due to outstanding collective phenomena, like the one producing superconductivity. The problem is that research in this field is limited by the fact QSLs are difficult to simulate with classical computers. Quantum computing can solve this problem by natively simulating QSLs. The challenge is therefore to define a Qbit architecture able to simulate QSLs and to explore potential materials and properties in line with SDGs.

Problem Statement:

A particular aspect of QSLs is a strong quantum entanglement, which cannot be simulated by classical computers. Quantum computing provides naturally the basic elements of quantum spin liquids by mapping Qbits exhibiting the quantum properties required for the simulation of those quantum states.

The solution of the challenge will lead to the development of new materials exhibiting quantum spin liquid properties. Quantum computers can also assist in **inverse design**: starting from desired properties (e.g., high-temperature superconductivity) and working backward to find candidate QSL materials.

Relevant Sustainable Development Goals (SDGs):

SDG 7 – Affordable and Clean Energy

QSLs may lead to breakthroughs in superconductivity, potentially enabling lossless energy transmission. This could drastically reduce energy waste in power grids and support the development of more efficient renewable energy systems.

QSLs could be used to design quantum materials **with tunable thermal and electrical properties**, useful in thermoelectric devices and energy harvesting.

The entanglement in QSLs might be harnessed for **quantum-enhanced energy storage**, potentially leading to faster charging and discharging cycle batteries.

SDG 9 – Industry, Innovation, and Infrastructure

QSLs are promising candidates for **topological quantum computing**, which is more robust against decoherence.

This could revolutionize industries by enabling faster, more secure computation and simulation of complex systems (e.g., drug discovery, climate modeling).

SDG 16 – Peace, Justice, and Strong Institutions

The entanglement properties of QSLs could be harnessed for **Quantum cryptography and ultra-secure communication systems**, enhancing cybersecurity and protecting sensitive data in governance and justice systems.

Role of Quantum Computing in Solving the Challenge:

Currently it is not possible to simulate quantum spin liquids with classical computing. Quantum computing works intrinsically with quantum bits which can reproduce the behaviour of quantum spin liquids and provide a unique way towards the development of new quantum materials like high temperature superconductors, etc.

Quantum Algorithms or Approaches:

- **Variational Quantum Eigensolver (VQE) –** Approximates ground states of QSL Hamiltonians.
- **Quantum Approximate Optimization Algorithm (QAOA) –** Simulates dynamics and frustration in spin systems.
- **Quantum Phase Estimation (QPE) –** Precisely estimates energy levels and phase transitions.
- **Tensor Network-Inspired Circuits –** Efficiently represent entangled QSL states.
- **Quantum Monte Carlo (QMC) –** Simulates thermal and quantum fluctuations (potentially on quantum hardware).
- **Hamiltonian Simulation –** Models time evolution of QSL systems (e.g., Trotterization, LCU).
- **Adiabatic Quantum Computing (AQC) –** Prepares QSL ground states via slow Hamiltonian evolution.

Preliminary Resources for Participants:

Key Research Articles

Spin liquids in frustrated magnets (Nature, 2010)

Probing Topological Spin Liquids on a Programmable Quantum Simulator (Science, 2021)

- Demonstrates the use of a 219-atom Rydberg atom array to simulate QSLs on a kagome lattice.
- Explores topological string operators and quantum correlations.

Digital Quantum Simulation of Spin Models with Circuit QED (Phys. Rev. X, 2015)

- Uses superconducting qubits to simulate Heisenberg and Ising models.
- Lays the groundwork for simulating more complex spin systems liquids

Courses and Learning Platforms

Quantum Spin Liquid Courses – Class Central

- Aggregates free and paid courses from platforms like Coursera, edX, and YouTube.
- Topics include topological order, Kitaev models, and quantum magnetism

MIT OpenCourseWare – Quantum Physics III

- Covers many-body quantum systems and spin models.
- Good theoretical foundation for understanding QSLs.

Qiskit Textbook – IBM Quantum

- Offers tutorials on quantum simulation, variational algorithms, and quantum chemistry.

Videos and Lectures

YouTube – Lectures by Subir Sachdev and Ashvin Vishwanath

- These leading researchers often post talks on QSLs, topological phases, and quantum simulation.