Usage Report for Fiscal Year 2024

Project Title:

Quantum spin liquid induced by magnetic fields in kagome antiferromagnets

Name:

○Yixuan Huang (1)

Laboratory at RIKEN:

(1) RIKEN Center for Emergent Matter Science, Computational Quantum Matter Research Team

1. Background and purpose of the project, relationship of the project with other projects

The quantum spin liquids are novel quantum states with long-range entanglement and emergent fractionalized excitations, which realize the spin analog of the fractional quantum Hall states. However, to date there are very few candidates of the quantum spin liquid in materials. Recently, there have been extensive developments on the kagome Mott insulators which accommodates a flat band with enhanced interaction effects. The experimental realization of single crystalline kagome Mott insulators like $ZnCu_3(OH)_6Cl_2$ and $ZnCu_3(OH)_6FBr$ has provided an opportunity to explore possible quantum spin liquids in those materials.

We study the extended spin-1/2 kagome Heisenberg model using numerical Density Matrix Renormalization Group methods, and search for the quantum spin liquids in a 1/9 magnetization plateau state. We identify the nature of the spin liquids through magnetic orders and non-zero Chern number.

Recently there have been many studies of the 1/9 magnetization plateau state on the kagome lattice because of its experimental realization in $YCu_3(OD)_{6+x}Br_{3-x}$ ($x \approx 0.5$). However, the true nature of the ground state in the 1/9 magnetization plateau remains an open question. The realization of quantum spin liquids will provide a crucial step towards the theoretical understanding of unconventional superconductivity by doping a spin liquid.

2. Specific usage status of the system and calculation method

We use numerical Density Matrix Renormalization Group methods to calculate finite size lattices in a cylinder geometry. The numerical algorithm is implemented through the open-source package ITensor (https://itensor.org). The ground state searches are performed variationally through the eigenvalue solver. The chiral spin liquids are numerically identified through the entanglement spectrum and the quantized spin pumping via flux insertion through the cylinder.

We have used all allocations for the mpc partition and most of the allocation for the lmc partition.

3. Result

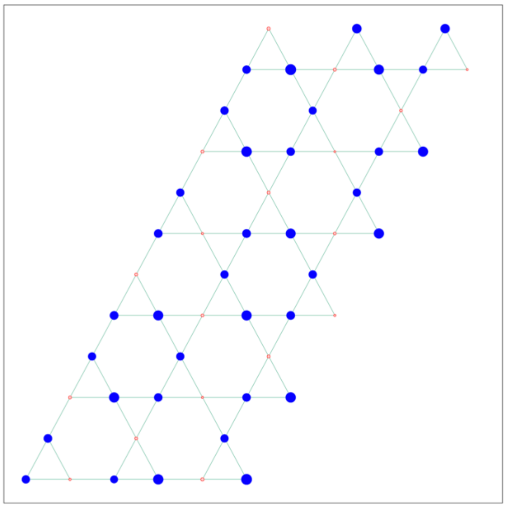
The ground state at 1/9 magnetization seems to break translational symmetry with enlarged unit cells and a valence bond crystal. In comparison, the chiral spin liquids at 1/3 and 0 magnetization does not break any translational symmetry. The chiral spin liquids at 0 magnetization can be realized with only z-component interactions or easy-axis interactions, while the chiral spin liquids at 1/3 can be realized with only z-component interactions.

We have tested various types of extended Heisenberg Hamiltonian focusing on the 1/9 magnetization plateau state on the kagome lattice. As suggested by the chiral spin liquid state in the triangular Hubbard model and Heisenberg model, we tested the different combinations of further neighboring interactions, anisotropic interactions, DM interactions, chiral interactions, and tuning the strength on the y-direction bonds.

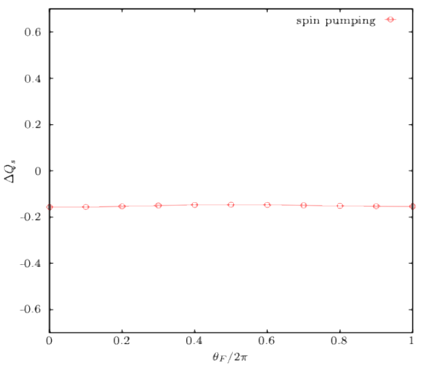
To characterize the chiral quantum spin liquids, we use the entanglement spectrum and spin flux insertion to obtain the spin pumping. To accommodate the translational symmetry breaking and enlarged unit cell, we try to implement the momentum space numerical DMRG algorithm.

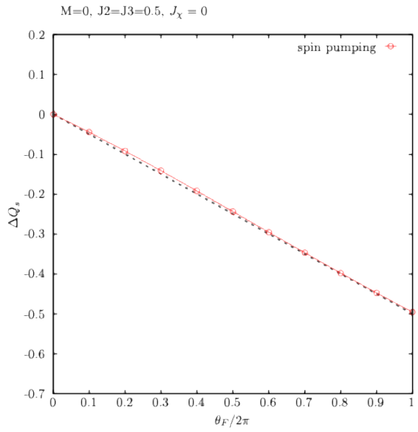
4. Conclusion

We found that the nearest neighbor Heisenberg model on the kagome lattice has several competing ground states with different magnetic orders. The magnetic order breaks translational symmetry, which can be seen in the figure below. Here the blue circle represents the positive spin value and red circle represents the negative spin value.

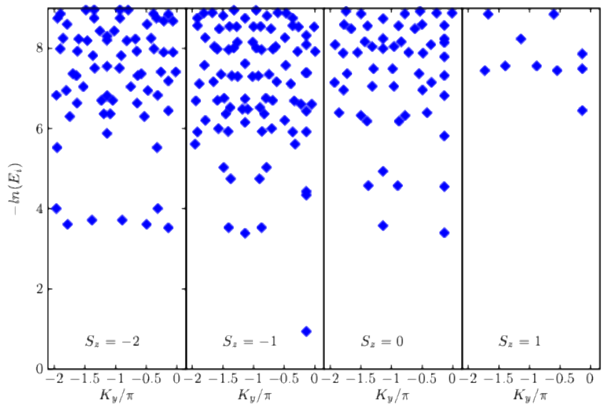


As a result, there is no finite chiral order and no spin pumping with spin flux insertion at 1/9 magnetization (top figure). As comparison, the quantized pumping can be found at 0 magnetization (bottom figure).





For the entanglement spectrum, the allowed discrete momentum becomes fewer due to the enlarged unit cell, and the error becomes larger when the spectrum is calculated, as shown in the figure below.



Therefore, it is hard to characterize the chiral spin liquid state using the degenerate pattern of the entanglement spectrum. However, we found that the spin flux insertion can still be used to determine the chiral spin liquids, and the nearest neighbor Heisenberg model at the 1/9 magnetization may be close to a chiral spin liquid state.

5. Schedule and prospect for the future

We will continue to search for the quantum spin liquids in the kagome lattice with a finite magnetization and study the nature of the quantum spin liquids using topological entanglement entropy, and identify its spin Chern number. Then, we will calculate the evolution of the magnetic order as a function of the coupling parameters to map out the quantum phase diagram.

After that we will compare our results with other numerical studies of the ground state at the 1/9 magnetization plateau, and try to calculation larger lattice sizes to obtain consistent results. At the same time, we will write a paper for publication in peer-reviewed journals.