A Quantum Antiferromagnet on the Kagomé Lattice

Featured papers:

1. `cond-mat/0610539` Spin Dynamics of the spin-1/2 Kagomé lattice antiferromagnet $ZnCu_3(OH)_6Cl_2$. *Authors:* J.S. Helton, K. Matan, M.P. Shores, E.A. Nytko, B.M. Bartlett, Y. Yoshida, Y. Takano, A. Suslov, Y. Qiu, J.-H. Chung, D.G. Nocera, Y.S. Lee [Phys. Rev. Lett. 98, 107204 (2007)]

2. `cond-mat/0610540` Ground state and excitation properties of the quantum kagomé system $ZnCu_3(OH)_6Cl_2$ investigated by local probes. *Authors:* O. Ofer, A. Keren, E. A. Nytko, M. P. Shores, B. M. Bartlett, D. G. Nocera, C. Baines, A. Amato.

3. `cond-mat/0610565` Quantum magnetism in the paratacamite family: towards an ideal Kagomé lattice. *Authors:* P. Mendels, F. Bert, M.A. de Vries, A. Olariu, A. Harrison, F. Duc, J.C. Trombe, J. Lord, A. Amato, C. Baines [Phys. Rev. Lett. 98, 077204 (2007)]

4. `cond-mat/0703141` ^{63}Cu and ^{35}Cl NMR Investigation of the $S = 1/2$ Kagomé Lattice System $ZnCu_3(OH)_6Cl_2$ *Authors:* T. Imai, E. A. Nytko, B.M. Bartlett, M.P. Shores, D. G. Nocera

Recommended with a commentary by Ashvin Vishwanath, UC Berkeley

Magnetism in geometrically frustrated lattices has been a topic of continuing interest for over five decades now. Frustration implies that wide variety of classical spin configurations are energetically equivalent on such lattices, although they are unrelated by any symmetry. Weak perturbations can therefore play a decisive role in determining the ground state. Also, thermal and quantum fluctuations which are generally associated with destroying order, can select states which optimize such fluctuations (order-by-disorder). Finally, frustrated spin systems have long been proposed as promising candidates for exotic quantum ground states.

The Kagomé lattice, a two dimensional lattice of corner sharing triangles named for a type of basket-weave, is perhaps the most intriguing frustrated lattice. On a single triangular face of the lattice, classical spins can take up a low energy configuration by making an angle of 120^0 with respect to one another. However, there are many different ways of extending this pattern across the lattice, leading to a huge degeneracy of classical ground states. The ground state of *quantum* spins on such a lattice has been widely debated. What is the state obtained on cooling a system of, say, spin 1/2 on the Kagomé lattice down to low temperatures? One possible scenario is that the system shows glassy behavior and drops out of thermodynamic equilibrium on cooling, an outcome known to occur in other frustrated magnets. If the system remains in thermal equilibrium, a wide variety of possible ground states have been theoretically considered. These range from magnetically ordered ground states, to valence bond solid ground states which break lattice symmetries and exhibit a spin gap, to more exotic 'spin-liquid' ground states that break no symmetries, both with and without a spin gap.

The recent synthesis [1] of $ZnCu_3(OH)_6Cl_2$ (or *herbertsmithite*), made of well separated planes of structurally undistorted Kagomé lattices, with spin 1/2 Cu moments, is hence an exciting development. While higher spin compounds on the Kagomé lattice have been studied earlier (eg. the iron jarosites [2], with spin 5/2), and spin-1/2 systems on distorted Kagomé lattices have also been identified (eg. volborthite, made of corner sharing isoceles triangles[3]) this is the first structurally perfect spin 1/2 Kagomé system. Experimentally, the one fly in the ointment in these systems is the possible presence of a small fraction of Cu impurity atoms replacing the nonmagnetic sites between the Kagomé planes. The compound is prepared from the parent compound clinoatacamite $Cu_4(OH)_6Cl_2$ (itself an interesting system), where the Cu spin 1/2 moments form a distorted pyrochlore lattice, which can be naturally separated into Kagomé planes with interleaving triangular lattice planes. When 1/4 of the Cu atoms are replaced with non magnetic Zn atoms, which take up all the triangular lattice sites, the weakly coupled spin 1/2 Cu Kagomé planes of herbertsmithite result. However in this process, a fraction (less than a few percent) of Cu atoms may enter the Zn planes and vice versa, although the former is believed to be more likely.

The featured references have brought a wide array of probes to bear on this Kagomé system - bulk magnetic susceptibility and specific heat, muon spin rotation and NMR, as well as inelastic neutron scattering on powder samples. The conclusions of these different studies are in broad agreement with one another and are as follows.

1. No evidence of spin freezing or glassy behavior is observed, for example in muon spin rotation or NMR, down to the lowest temperatures studied [50 mKelvin].

2. Although the exchange constant is estimated to be $J = 170K - 200K$, no magnetic

ordering is observed down to the lowest temperatures [50 mKelvin $\approx$ J/3000]. Also, no finite temperature phase transition is seen in the specific heat.

3. While both these conclusions were anticipated by numerical studies of small Kagomé systems, those studies also predicted a spin-gap but with many low lying spin-singlet excitations. At temperatures below the spin-gap energy scale, a drop in spin susceptibility is expected. Surprisingly, no sign of a spin gap is seen in the experiments. For example, the bulk magnetic susceptibility is found to be gradually *increasing* with decreasing temperature, down to about 200mK. This is also corroborated by susceptibility measurements using muon spin rotation, which points to a bulk origin for this susceptibility, since muons can readily distinguish an impurity signal. Similarly, inelastic neutron scattering and $1/T_1$ NMR measurements provide evidence for low energy magnetic excitations.

It is quite remarkable that such low energy scales arise in a strongly quantum model. The behavior of this material is unusual even by the standards of frustrated magnets. Experimentally, further quantitative characterization of low energy excitations would be very useful. On the theoretical side, in addition to ideas for describing the low energy excitations, the role played by impurity spins and the Dzyaloshinskii-Moriya (DM) interaction [4] need to be accounted for. The latter is known to play an important role in determining the ordered state in iron jarosite [2], a higher spin analogue of the present compound. In the presence of D-M interaction the total spin is no longer conserved, which needs to be kept in mind while interpreting experimental results.

Insulating magnets are perhaps the simplest many body quantum systems to address theoretically and also numerically. In that respect, we are in as strong a position as we could possibly be, to understand these striking experimental phenomena more deeply. Such an understanding might also impact our foundational concepts of quantum many body physics.

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[3] Z. Hiroi, M. Hanawa, N. Kobayashi, M. Nohara, H. Takagi, Y. Kato, and M. Takigawa, J. Phys. Soc. Jpn. **70**, 3377 (2001).

[4] M. Rigol and R. R. P. Singh, cond-mat/0701087 (2007).