Ground states of quantum kagomé antiferromagnets in a magnetic field

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We study the ground state properties of a quantum antiferromagnet in the kagomé lattice in the presence of a magnetic field, paying particular attention to the stability of the plateau at magnetization 1/3 of saturation. While the plateau is reinforced by certain deformations of the lattice, like the introduction of structural defect lines and against an Ising anisotropy, ground state correlations are seen to be quite different and the undistorted SU(2) case appears to be rather special.

The interest in the study of quantum two-dimensional frustrated antiferromagnets has been boosted by recent high magnetic field experiments where different exotic situations have been observed. Generically, plateaux and jumps in the magnetization curve show up in materials realizing different frustrated structures.\cite{1,2,3}

In the case of the kagomé lattice, the nature of the ground state at zero field shows interesting features of a disordered spin liquid with a spin gap and a macroscopic number of low lying (spinless) excitations.\cite{4,5,6,7} There is general consensus in that this lattice shows a clear plateau at magnetization 1/3 of saturation\cite{8} and that in this case the spin gap is larger than in the zero field case, making it more stable and potentially observable.

Prompted by these findings, we studied the antiferromagnetic (AF) Heisenberg model defined on the kagomé lattice focusing at the spinful state with $M = 1/3$. We have allowed for different couplings along the different directions in the kagomé lattice and found that the plateau at 1/3 survives this distortion and it is even enhanced. On the other hand, the ordering of the GS changes substantially at the isotropic point, whose nature is still under debate.\cite{9}

Interestingly, our results also reveal the emergence of a whole regime ($J'/J < 0.62$), in which the spontaneous susceptibility diverges at $M = 1/3$, i.e. all lower fields vanish $\forall \ M \leq 1/3$. Recent magnetic field measurements in the novel cuprate Volborthite, Cu$_3$V$_2$O$_7$(OH)$_2$-2H$_2$O, which is apparently described by a distorted kagomé lattice like the one studied in the present paper, show no plateau at zero magnetization down to 1.8K. This could be taken as an indication that this material lies within the region of couplings slightly above $J'/J \sim 0.62$, where fairly small spin excitations are observed. If this turns out to be the case, this would imply that the predicted 1/3 plateau could be accessible to the magnetic fields currently available, since this plateau opens up for fairly small field values within this range of couplings.

Turning to the GS orderings, it is important to emphasize that all studied samples at $M = 1/3$ yield a rather small non-magnetic gap ($\Delta S^z = 0$) which is at least one order of magnitude smaller than the involved spin exchange interactions. We also observed that for $J'/J = 3/4$ the spin pair correlations $\langle \sigma^z_0 \sigma^z_r \rangle$ display long distance ferromagnetic (F) order along the $J'$-direction whereas the $J$-directions become clearly antiferromagnetic (AF), as is shown in Fig. 3 (We call this hereafter AF-F ordering). For $J'/J > 1$ these AF-F orderings directions result exchanged.

A completely different scenario arises when $J = J'$, where though non-magnetic excitations still remain very small, the radial average over pair correlation functions resembles the characteristics of a $\sqrt{3} \times \sqrt{3}$ spin liquid rather than those of an ordered state. However, further work is needed to understand the GS structure in the isotropic SU(2) case.\cite{10}

We have also studied the overlaps of the GS wave function with the real space $\sigma^z$-configurations. Specifically, Fig. 3 displays the probabilities $| \langle s | \psi \rangle |^2$ of these $| s \rangle$-states after sorting their weights on the $| \psi \rangle$ GS of a given cluster. The key issue here is that a clean probability scale separation -more than one order of magnitude-, shows up between the AF-F configuration and the rest of the GS components. However,
it should be stressed that the point $J = J'$ is special in that it exhibits an entirely different scenario. In that case the hierarchy of probability scales is smeared out completely and a much larger number of states seems to intervene on the pair correlations. The point here is that the maximum GS overlap can therefore be regarded as an alternative measure of order, so long as the hierarchical overlap distribution still holds.

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FIG. 2: Magnetization curves of different cluster sizes \( N \) obtained for \( N = 21 \) (dotted lines), \( 24 \) (dashed lines) and \( 27 \) spins (solid lines), using \( J'/J = 3/4 \).

FIG. 3: Ground state for \( J'/J = 0.9 \) at \( M = 1/3 \) for \( N = 27 \). Real space states in the \( \sigma^z \)-representation are sorted by increasing overlaps and normalized to their maximum value (only overlaps above \( 10^{-3} \) are shown). The latter corresponds to an AF-F state whose pair correlations \( C(n) \) along \( J \)-directions exhibit AF order as opposed to the F-order behavior along the \( J' \)-direction. This is respectively shown by the dashed and solid lines of the inset.