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Quantum Spin Liquid Induced by Frustration and Randomness

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Experimental quest for the hypothetical ``quantum spin liquid'' state recently met a few promising candidate materials on certain geometrically frustrated lattices such as the triangular and kagome lattices. The former includes organic salts κ-$(ET)_2Cu2(CN)_3$ and $EtMe_3Sb[Pd(dmit)_2]_2$, while the latter includes herbersmithite $CuZn_3(OH)_6Cl_2$. These spin-*1/2* compounds exhibit no magnetic ordering nor the spin freezing down to very low temperature, while the measured physical quantities mostly exhibit gapless behaviors. We argue that these compounds might contain significant amount of (effective) quenched randomness of varying origin, i.e., the freezing of the charge (dielectric) degrees of freedom in the case of triangular organic salts and the possible Jahn-Teller distortion accompanied by the random substitution of Zn^{2+} by Cu^{2+} in the case of herbertsmithite, which might be essential in stabilizing the quantum spin-liquid-like behaviors observed experimentally.

We propose as a minimal model the $S=1/2$ antiferromagnetic Heisenberg model on the triangular and the kagome lattices with a quenched randomness in the exchange interaction, and study both zero- and finite-temperature properties of the model by exact diagonalization and Hams-de Raedt methods ([1-3]). The randomness is introduced via the distribution width δ of the antiferromagnetic nearest-neighbor interaction with the mean J. We then find that, when the randomness δ/J exceeds a critical value, the model exhibits a quantum spin-liquid-like ground state with gapless behaviors, including the T-linear low-temperature specific heat as shown in Fig.1(left), and the gapless susceptibility often accompanied by the Curie tail as shown in Fig.1(right).

The low-temperature state is argued to be a ``random-singlet'' (or ``valence-bond-glass'') state, where local spin singlets of varying strengths are formed from bond to bond in a hierarchical manner, as schematically demonstrated in Fig.2. The state may also be viewed as sn “Anderson-localized” RVB (resonating-valence bond) state. The results seem to provide a consistent explanation of the recent experimental observations.

The calculation is further extended to other lattices even including bipartite ones such as the honeycomb ([4]) and square [5] lattices. The frustration is introduced via the antiferromagnetic next-nearest-interaction J_2, which competes with the main antiferromagnetic nearest-neighbor interaction J_1. The phase diagram of these model are constructed in the frustration J_2/J_1 versus the randomness δ plane and a variety of magnetic and non-magnetic phases are identified. The random-singlet state is then found to be stabilized in a wider range of the parameter space, demonstrating that this frustration and randomness induced “quantum spin liquid state”, though gapless in nature, might be stabilized quite generically over a wide range of systems so long as there exists certain amount of randomness or inhomogeneity whether it is extrinsic or self-generated.

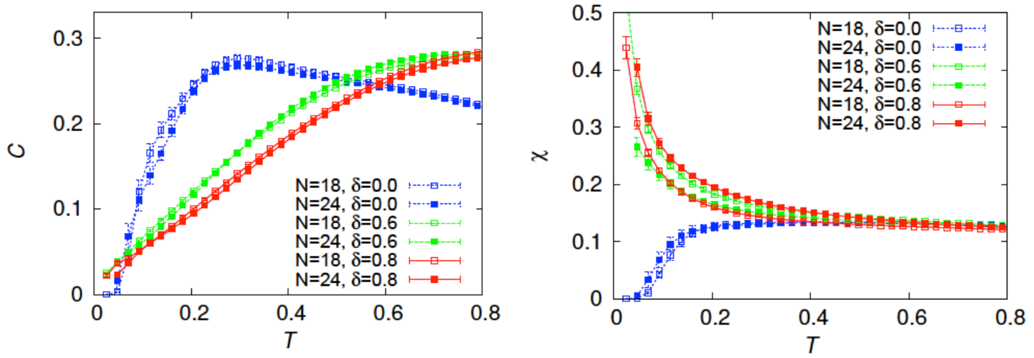

Fig.1: The low-temperature specific heat (left) and the low-temperature susceptibility of the random triangular model for values of the randomness δ and for several lattice sizes (total number of spins) N.

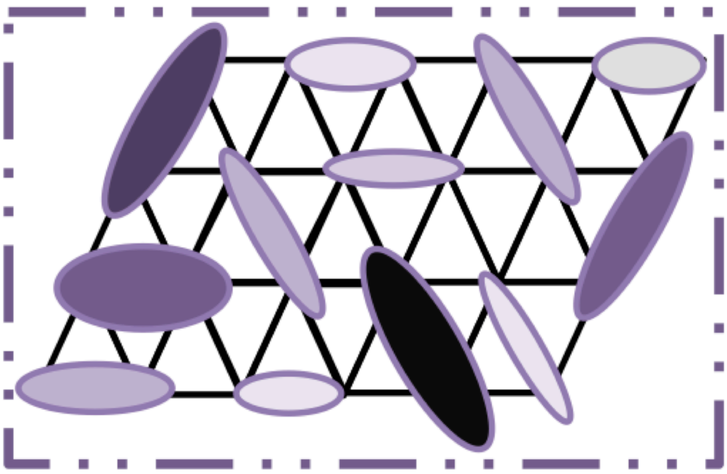

Fig.2: A schematic picture of the random-singlet state (the valence-bond glass state).

References

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