Title	Magnetic Properties of the Pyrochlore Lattice(New Developments in Strongly Correlated Electron Systems)
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Citation	物性研究 (2001), 76(5): 692-692
Issue Date	2001-08-20
URL	http://hdl.handle.net/2433/97042
Right	
Type	Departmental Bulletin Paper
Textversion	publisher

Magnetic Properties of the Pyrochlore Lattice

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Quantum antiferromagnetic spin system on the pyrochlore lattice is theoretically investigated. Since its classical ground state has a thermodynamic degeneracy, we may expect that quantum fluctuations play an essential role for lifting the degeneracy and low-energy magnetic properties are determined accordingly. I develop an approach to fully take account of local quantum fluctuations and find a hierarchy of energy scales that determine the successive lift of degeneracy.

I study the spin-1/2 Heisenberg model with antiferromagnetic nearest-neighbor couplings J. Considering the spin gap of this model is believed to be finite, I start from a quantum disorder fixed point. It is a set of decoupled tetrahedra each of which has doubly degenerate spin-singlet ground states with opposite chirality. Using a spin-1/2 pseudospin representation, I obtain an effective model for chirality degrees of freedom based on the third-order perturbation theory, and then determine its mean-field ground state. The result agrees with the proposal by Harris et al. [J. Appl. Phys. 68 (1991) 5200] and shows a long-range order of "transverse" component of chirality in three of the four sublattices. This corresponds to a triple-q structure of spin-singlet dimer pairs. The energy scale of this order, J^*, is substantially renormalized from the largest energy scale, i.e. the spin gap (a fraction of J). There remains residual thermodynamic degeneracy relating to pseudospins in the disordered sublattice. These pseudospins interact to each other via exchanging bosonic excitations in the ordered sublattices. The corresponding energy scale, $J^{\#}$, is calculated by means of a harmonic approximation for the bosonic excitations. I examine the symmetry of this effective couplings and found that all the pseudospins will ultimately show a $\mathrm{q} = 0$ long-range order of its transverse component.

The existence of multiple energy scales is a consequence of frustration effects in each level of description of the system. It is interesting that renormalization of the energy scales is solely determined by geometrical factors, rather than competition of several couplings with distinct origins.

I also study the relative stability of various types of classical magnetic order in the limit of $S \to \infty$. I estimate their zero-point energy associated with quantum fluctuations by means of the spin wave theory, and find that a collinear order has the lowest energy.