

## Chiral Ordered Phases in Frustrated Quantum Spin Chains

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We study the ground-state properties of a one-dimensional anisotropic spin system with the antiferromagnetic nearest-neighbor coupling  $J_1$  and the frustrating next-nearest-neighbor coupling  $J_2$ . The model Hamiltonian has the form,

$$\mathcal{H} = \sum_{\rho=1}^2 \left\{ J_{\rho} \sum_l (S_l^x S_{l+\rho}^x + S_l^y S_{l+\rho}^y + \Delta S_l^z S_{l+\rho}^z) \right\}, \quad (1)$$

where  $\vec{S}_l$  is a spin- $S$  spin operator at site  $l$ . We concentrate on the case of  $XY$ -like anisotropy  $0 \leq \Delta < 1$ . We are particularly interested in the possible gapless and gapped “chiral” phase, in which the  $z$ -component of the vector chirality  $\kappa_l = S_l^x S_{l+1}^y - S_l^y S_{l+1}^x$  exhibits a finite long-range order while the spin correlation decays either algebraically or exponentially. In the chiral phases, only the parity symmetry is broken spontaneously whereas the time-reversal and translational symmetries are preserved. It has been suggested by the bosonization approach with a mean-field approximation<sup>1,2</sup> that in the  $XY$  case ( $\Delta = 0$ ) the system for general  $S$  exhibits the gapless chiral phase for large  $j \equiv J_2/J_1$ .

In the presentation, we report the results of our study<sup>3,4,5</sup> in which the ground-state phase diagrams of model (1) are determined numerically for  $S = 1/2, 1, 3/2, 2$  using the density-matrix renormalization group method. The main results are summarized as follows.

- The gapless chiral phase appears in a broad region of the phase diagram for general  $S$ . By contrast, the gapped chiral phase is found for integer  $S$  in a narrow region between the Haldane and gapless chiral phases, while it has not been identified for half-odd integer  $S$  within our numerical accuracy.
- As  $S$  increases toward the classical limit  $S \rightarrow \infty$ , the region of the gapless chiral phase converges smoothly toward that of the classical helical phase,  $j > 1/4$  for  $0 \leq \Delta < 1$ .

We also present the ground-state phase diagram of the frustrated  $S = 1$  Heisenberg chain with uniaxial single-ion-type anisotropy.

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<sup>3</sup> M. Kaburagi *et al.*, J. Phys. Soc. Jpn. **68**, 3185 (1999).

<sup>4</sup> T. Hikihara *et al.*, J. Phys. Soc. Jpn. **69**, 259 (2000).

<sup>5</sup> T. Hikihara *et al.*, cond-mat/0010283, to appear in Phys. Rev. B.