Magnetic Hedgehog Lattice in a Centrosymmetric Cubic Metal

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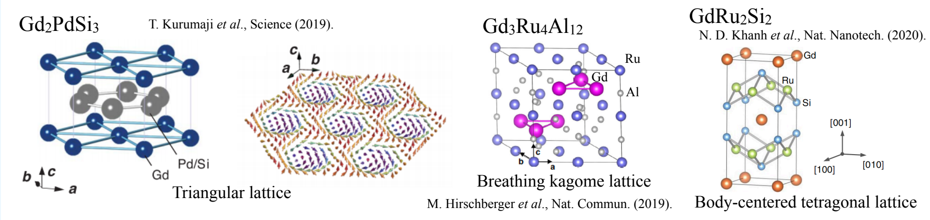
Introduction Multiple-*Q* spin textures in *centrosymmetric* metals without the DMI

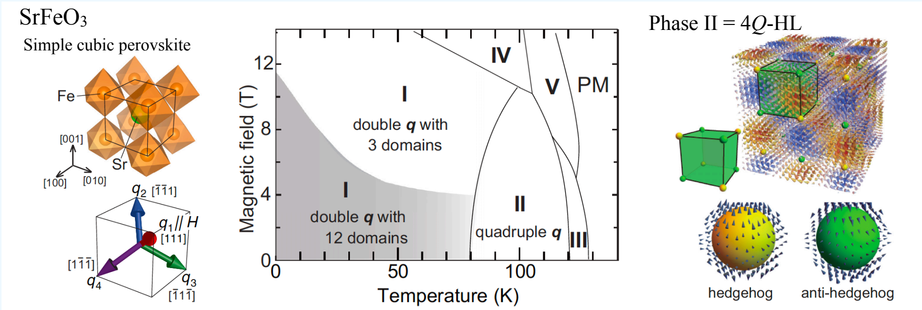
❑ 2D 3*Q* skyrmion lattice (3*Q*-SkL)



✓ The short-period magnetic structures lead to the large topological Hall effect.

✓ These 3*Q*-SkLs can be stabilized by magnetic frustrations or the effect of itinerant electrons without the Dzyaloshinskii-Moriya interaction (DMI). T. Okubo *et al.*, PRB (2012), R. Ozawa *et al.*, PRL (2017).

❑ 3D 4*Q* hedgehog lattice (4*Q*-HL) S. Ishiwata *et al.*, PRB (2011), S. Ishiwata *et al.*, PRB (2020).



✓ The phase II (4*Q*-HL) exhibits the topological Hall effect similar to the 3*Q*-SkL.

✓ The stabilization mechanism of the 4*Q*-HL in a centrosymmetric system is unclear thus far.

cf. a noncentrosymmetric system with the DMI → S. Okumura *et al.*, PRB (2020).

Purpose of this study

To clarify the origin of the hedgehog lattice in a centrosymmetric metal from a microscopic viewpoint, especially by taking into account the effect of itinerant electrons.

Model

3D *s*-*d* model for generic magnetic metals

$$\mathscr{H} = \sum_{\mathbf{k}\sigma} (\varepsilon_{\mathbf{k}} - \mu) c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + J_{\mathrm{K}} \sum_{\mathbf{k}\mathbf{q}\sigma\sigma'} c^{\dagger}_{\mathbf{k}\sigma} \boldsymbol{\sigma}_{\sigma\sigma'} c_{\mathbf{k}+\mathbf{q}\sigma'} \cdot \mathbf{S}_{\mathbf{q}} - \sum_{l} \mathbf{h} \cdot \mathbf{S}_{l}$$

4th-order perturbation expansion with respect to J_{K}

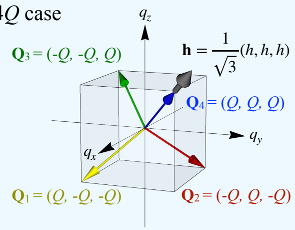
S. Hayami *et al.*, PRB (2017).

Effective spin model with *q*-dependent interactions

$$\mathscr{H}_{\mathrm{eff}} = 2 \sum_{\eta} \left[-J \mathbf{S}_{\mathbf{Q}_\eta} \cdot \mathbf{S}_{-\mathbf{Q}_\eta} + \frac{K}{N} (\mathbf{S}_{\mathbf{Q}_\eta} \cdot \mathbf{S}_{-\mathbf{Q}_\eta})^2 \right] - \sum_{l} \mathbf{h} \cdot \mathbf{S}_{l}$$

bilinear interaction ($\sim J_{\mathrm{K}}^2$) positive biquadratic interaction ($\sim J_{\mathrm{K}}^4$)

Ordering vectors for the tetrahedral 4*Q* case



✓ This effective spin model can be used as a generic phenomenological model.

✓ In the following calculations, we take $J = 1$, $\mathbf{h} = \frac{1}{\sqrt{3}}(h, h, h)$, $Q = \frac{\pi}{4}$, and $N = 16^3$.

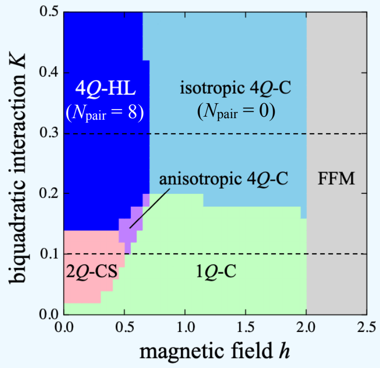
Method

Simulated annealing S. Okumura *et al.*, JPS Conf. Proc. (2020).

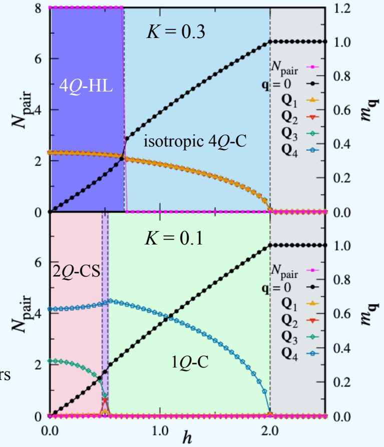
We investigate the ground states of the effective spin model by performing Monte Carlo simulations with the standard Metropolis algorithm, gradually decreasing temperature T from 1 to 10^{-5} with 10^4 Monte Carlo sweeps at each T.

Results

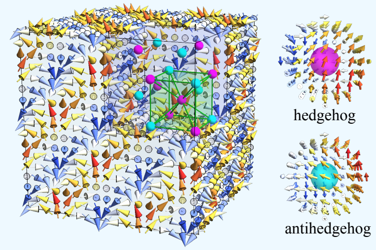
S. Okumura, S. Hayami, Y. Kato, and Y. Motome, in preparation.

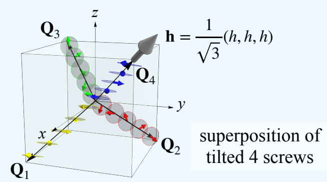


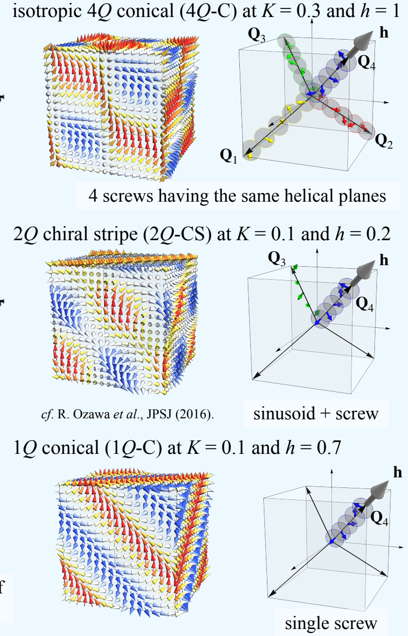
N_{pair} : the number of hedgehog-antihedgehog pairs



4*Q*-HL at $K = 0.3$ and $h = 0$







The 4*Q*-HL is stabilized due to the synergy between the bilinear and biquadratic interactions even in the absence of the Dzyaloshinskii-Moriya type interaction in a centrosymmetric system.

Discussion

◎ 2*Q*→1*Q* phase transition at $T \sim 0$ ⇒ The 2*Q*-CS is also stabilized by the *d*-*p* model imitating $SrFeO_3$. R. Yambe and S. Hayami, JPSJ (2020).

○ 4*Q*→1*Q* phase transition expected by increasing *T*

⇒ The entropic effect can enhance the 4*Q*-HL similar to the biquadratic interaction *K*. T. Okubo *et al.*, PRB (2011).

△ No net scalar spin chirality in the magnetic field

⇒ The directions of the helical planes play an important role in the topological Hall effect.

※ The local spin rotation around the field direction is allowed in our model without any anisotropic terms.

→ The types of the constituent waves can be changed by cubic and bond-dependent anisotropy. S. Hayami and Y. Motome, PRB (2021).

Summary

❑ We clarified that the 4*Q*-HL is stabilized in the centrosymmetric system by using simulated annealing for the effective spin model including the bilinear and biquadratic interactions without the DMI.

❑ We found the 2*Q*-1*Q* and 4*Q*-1*Q* phase transitions while increasing the magnetic field, which might correspond to the low-*T* and high-*T* experimental results in $SrFeO_3$, respectively.

Perspective

✓ To include the effects of temperature and anisotropy in order to reproduce the phase diagram in $SrFeO_3$.

✓ To investigate transport properties and dynamics unique to the centrosymmetric HL.