Topological magnetoelastic excitations in triangular antiferromagnets

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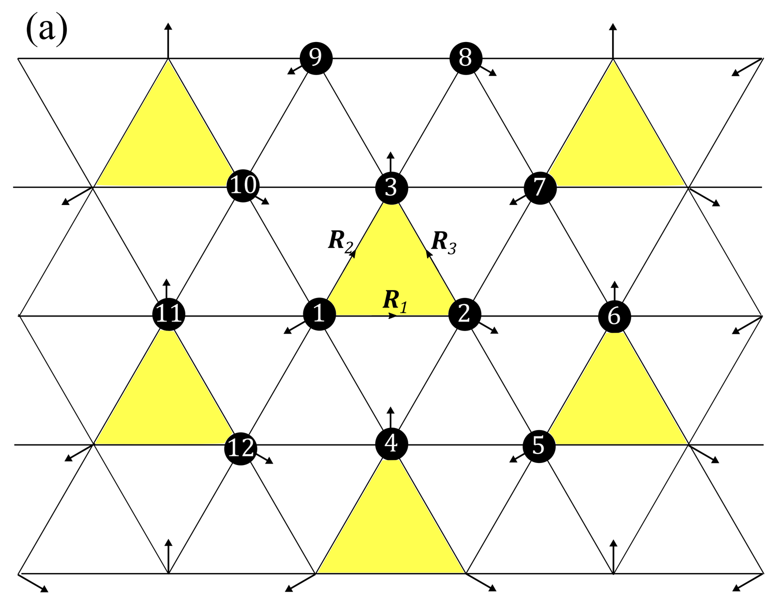
Motivation: can non-zero Chern number arise from magnon-phonon coupling?

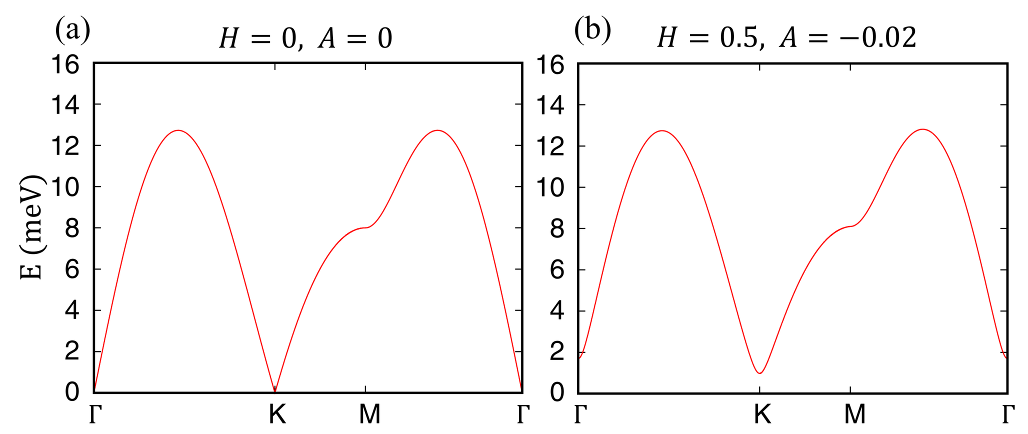
- Topological magnon (R. Shindou et al PRB 2013) and topological phonon (L. Zhang et al PRL 2010) bands with non-zero Chern number implies existence of chiral edge states and non-zero thermal Hall conductivity.
- Magnon and phonon can naturally hybridize due to magnon-phonon coupling, with large Berry curvature at anticrossing region (Takahashi, Nagaosa PRL 2016)
- We give a toy model on triangular antiferromagnet where topologically trivial magnon and phonon hybridize to form topologically nontrivial magnetoelastic bands.
- Magnon-phonon interaction can modify the thermal Hall conductivity.



Magnon

$$\mathcal{H}_m = \mathcal{H}_J + \mathcal{H}_A + \mathcal{H}_H$$

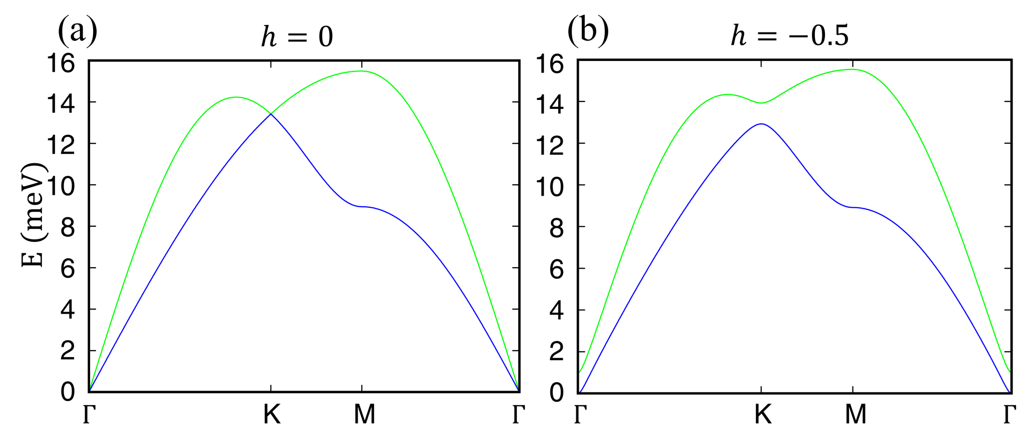
- $\mathcal{H}_J$ Nearest neighbor Heisenberg
- $\mathcal{H}_A$ Anisotropy
- $\mathcal{H}_H$ Zeeman coupling



Phonon

$$\mathcal{H}_p = \frac{1}{2}\sum_{\alpha\beta\boldsymbol{R}\boldsymbol{R}'}[\{\boldsymbol{p}_\alpha(\boldsymbol{R})^2 + 2\boldsymbol{u}_\alpha(\boldsymbol{R})A_{\alpha\alpha}\boldsymbol{p}_\alpha(\boldsymbol{R})\}\delta_{\alpha\beta}\delta_{\boldsymbol{R},\boldsymbol{R}'} + \boldsymbol{u}_\alpha(\boldsymbol{R})\{K_{\alpha\beta}(\boldsymbol{R}-\boldsymbol{R}') - (A^2)_{\alpha\beta}\}\boldsymbol{u}_\beta(\boldsymbol{R}')].$$

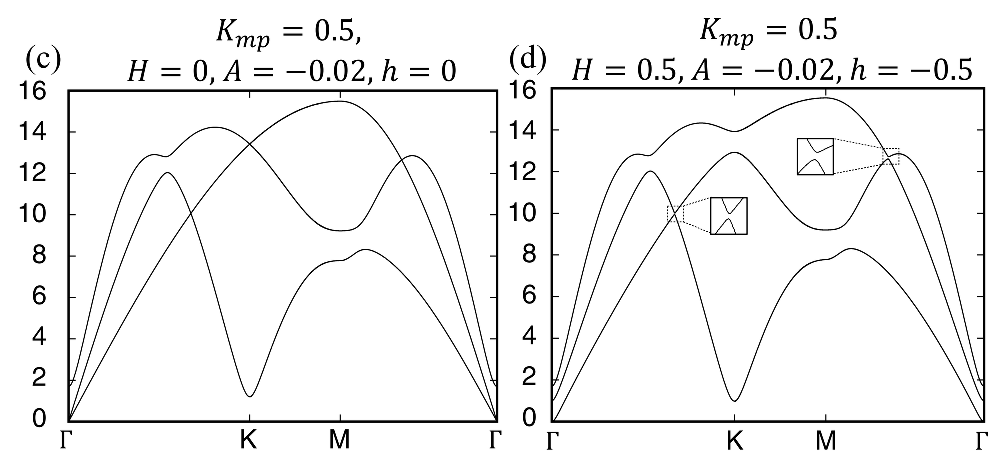
- Nearest Neighbor spring constant and Phenomenological Raman coupling



Magnon-phonon coupling

$$\mathcal{H}_c = \sum_{\langle ij\rangle} K_{mp}\boldsymbol{R}_{ij}\cdot\Delta\boldsymbol{u}_{ij}\boldsymbol{S}_i\cdot\boldsymbol{S}_j$$

- Exchange striction: $J(|\boldsymbol{r}_i - \boldsymbol{r}_j|) \approx J + K_{mp}\boldsymbol{R}_{ij}\cdot\Delta\boldsymbol{u}_{ij}$,
- where $\boldsymbol{r}_i = \boldsymbol{R}_i + \boldsymbol{u}_i$



Berry curvature and Chern number

- Large Berry curvature is induced from magnon-phonon coupling
- Although the magnon-phonon Hamiltonian is often written using the fields

$$\Psi_{\boldsymbol{k}} = (a_{\boldsymbol{k}}, b_{1,\boldsymbol{k}}, b_{2,\boldsymbol{k}}, a^\dagger_{-\boldsymbol{k}}, b^\dagger_{1,-\boldsymbol{k}}, b^\dagger_{2,-\boldsymbol{k}}),$$

  where a's are Holstein Primakoff operators and b are phonon operators, this does not give the correct Berry curvature.
- We should write the Hamiltonian using

$$\Phi_{\boldsymbol{k}} = \left(a_{\boldsymbol{k}}, a^\dagger_{-\boldsymbol{k}}, \boldsymbol{p}^T_{\boldsymbol{k}}, \boldsymbol{u}^T_{\boldsymbol{k}}\right)$$

- Then, $\Sigma_{\boldsymbol{k}} \equiv PV^\dagger\Phi_{\boldsymbol{k}}$ is bosonic BdG field:

$$[\Sigma_{\boldsymbol{k},i}, \Sigma_{\boldsymbol{k},j}] = (\sigma_z)_{ij}, \qquad \Sigma_{-\boldsymbol{k}} = \sigma_x\Sigma^\dagger_{\boldsymbol{k}}$$

$$P = \begin{pmatrix} I_1 & & & \\ & & I_2 & \\ & I_1 & & \\ & & & I_2 \end{pmatrix}, \quad V = \begin{pmatrix} I_2 & & \\ & \frac{1}{\sqrt{2}}I_2 & \frac{1}{\sqrt{2}}I_2 \\ & \frac{i}{\sqrt{2}}I_2 & \frac{-i}{\sqrt{2}}I_2 \end{pmatrix}$$

Phonon

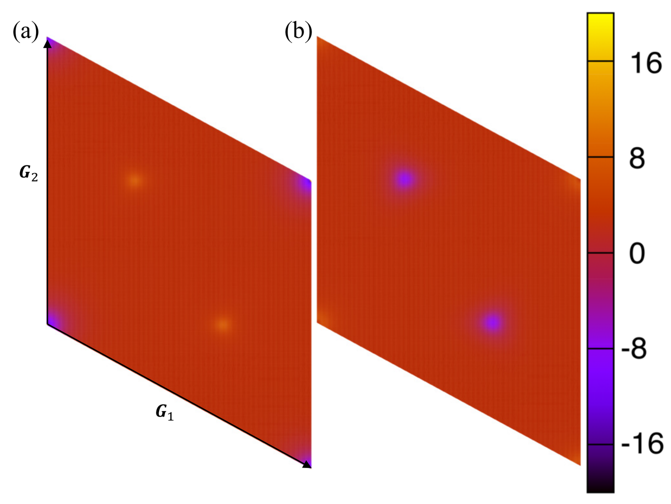


Fig. Caption
Phonon Berry curvature induced by Raman interaction

Magnetoelastic

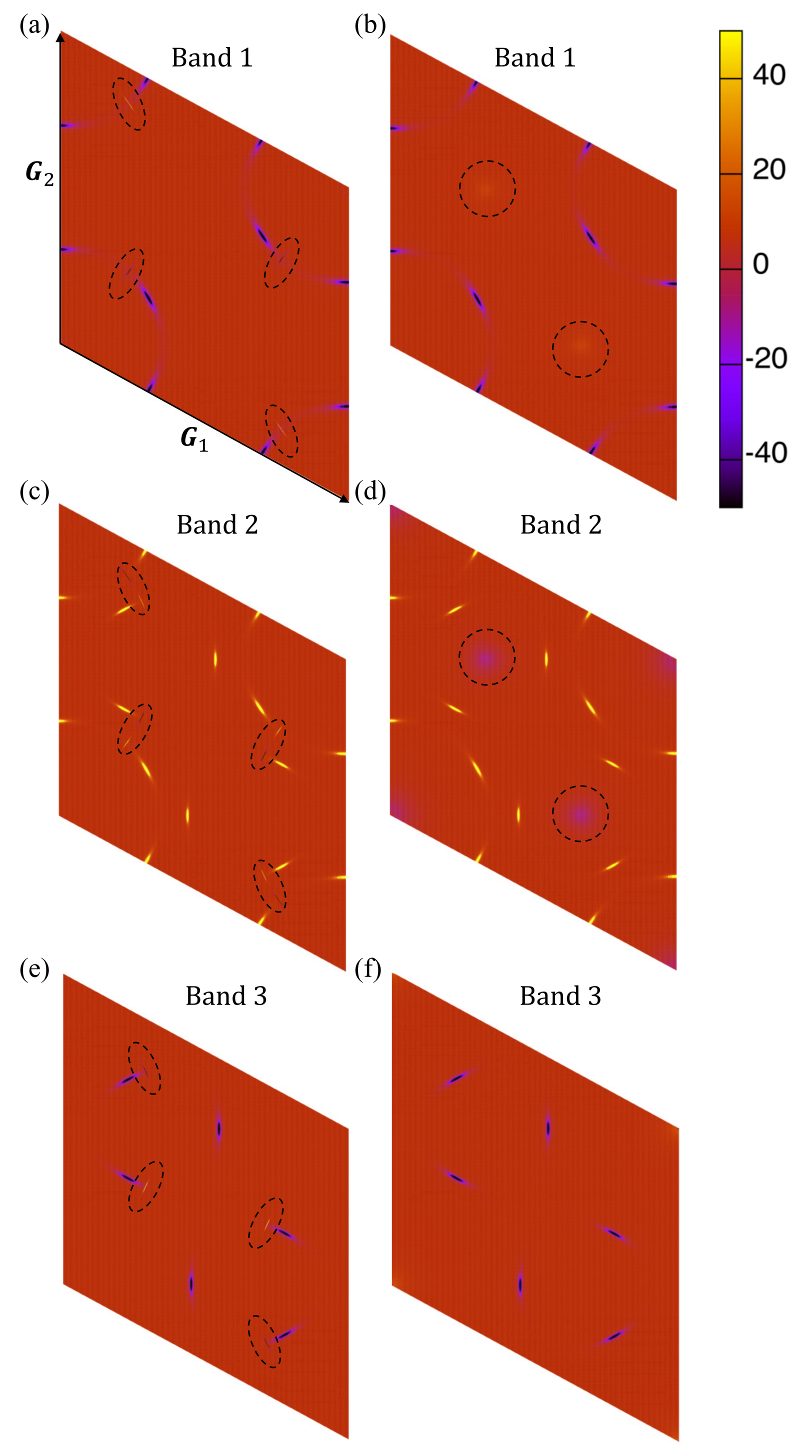


Fig. Caption
(a), (c), (e): Berry curvatures calculated by using field $\Psi_{\boldsymbol{k}}$
(b), (d), (f): Berry curvatures calculated by using field $\Sigma_{\boldsymbol{k}}$

Note that the phonon Berry curvature is missed in (a), (c), and (e).

The Hamiltonian written using $\Psi_{\boldsymbol{k}}$ does not have to be smooth, which results in unphysical singularities in Berry curvature.

The Chern numbers for (b), (d), and (f) are -2, 4, -2 respectively.

Thermal Hall conductivity

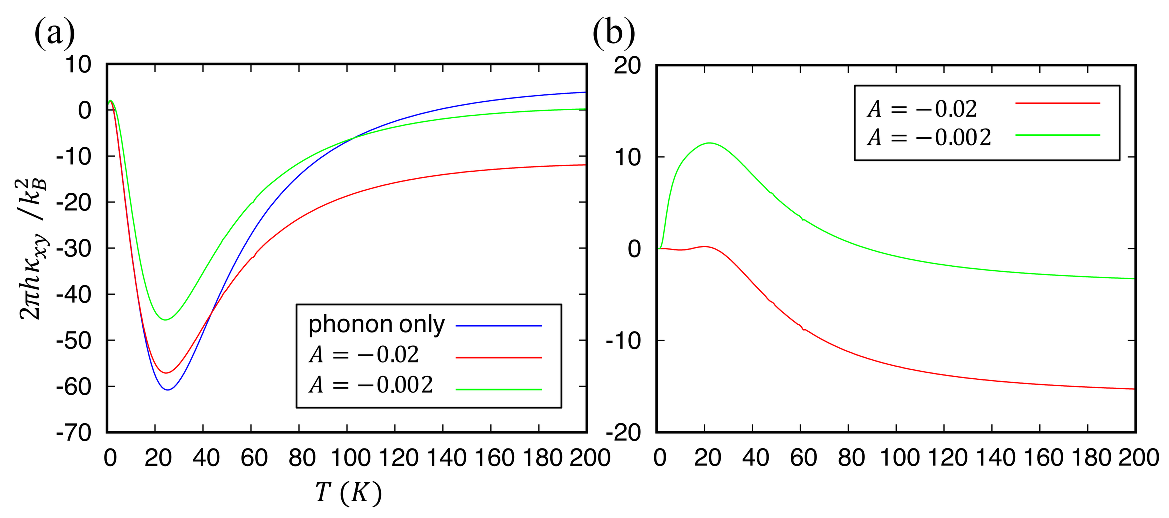
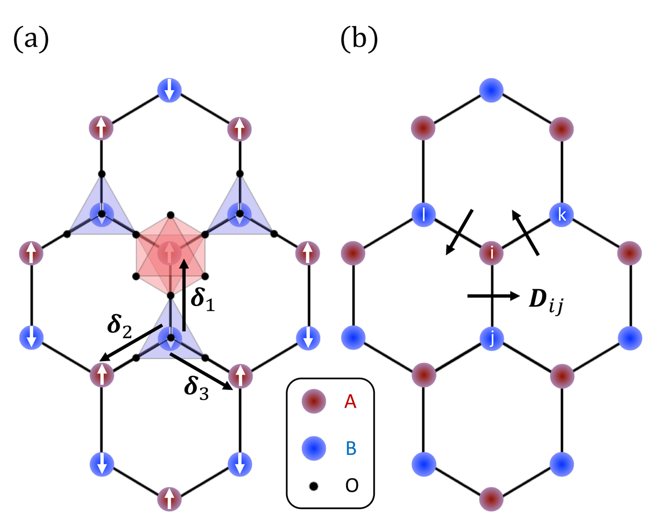


Fig. Caption:
Left: thermal Hall conductivity computed using Berry curvatures calculated by using field $\Sigma_{\boldsymbol{k}}$
Right: thermal Hall conductivity computed using Berry curvatures calculated by using field $\Psi_{\boldsymbol{k}}$

Spin Current?

- Consider a collinear antiferromagnet.
- The magnon bands carry spin quantum numbers
- The magnon-phonon interaction can induce thermal Hall and spin Nernst current



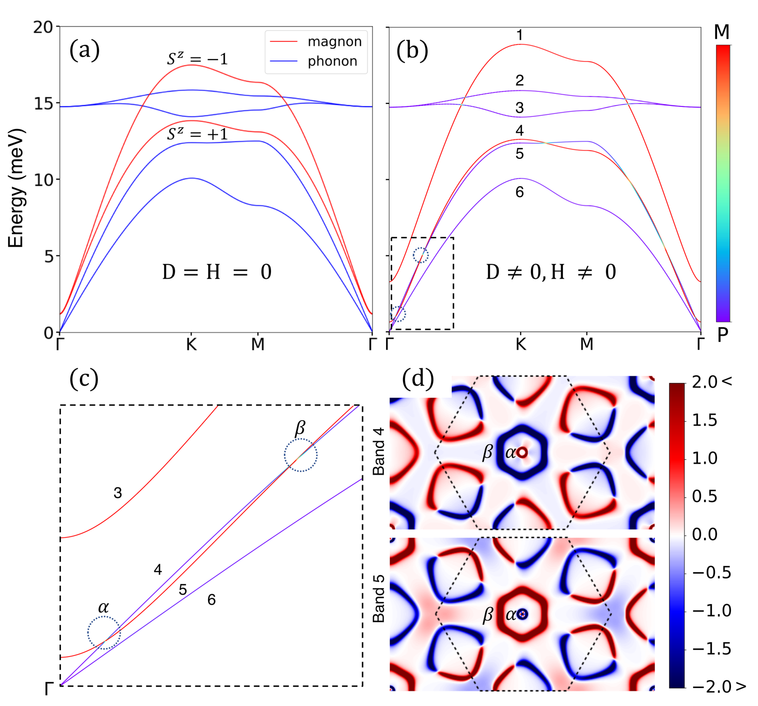
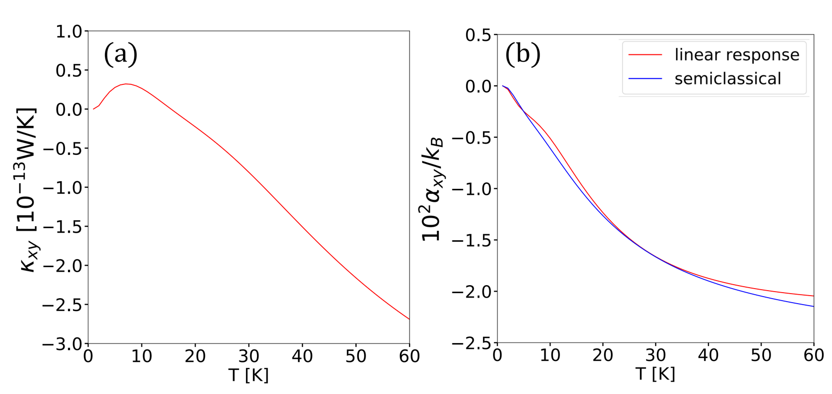


Fig. Caption
Energy spectrum and Berry curvature



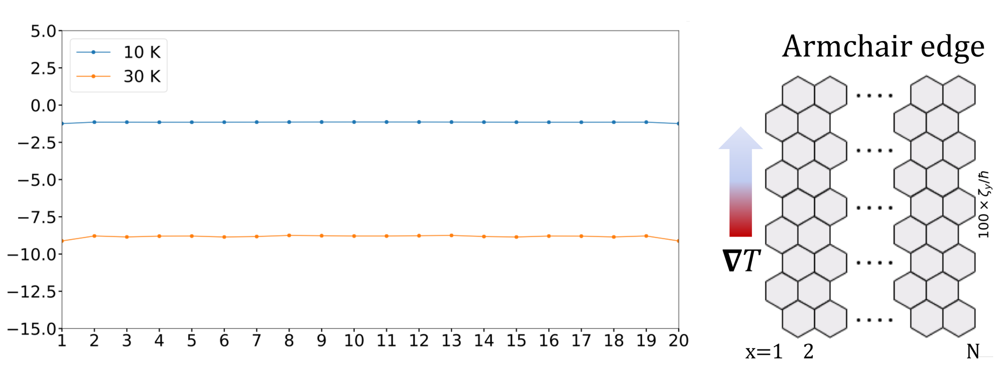


Fig. Caption
Top: Thermal Hall and spin Nernst conductivity
Bottom: spin density

Nontrivial bulk boundary correspondence between the spin Nernst current and the edge spin accumulation

Thermal gradient induces (bulk) spin density, which is allowed because magnon-phonon interaction violates spin conservation.