Chiral Spin Textures Driven by Emergent Spin-Orbit Interaction: A Numerical Study

Shuai Yang[1], Zhi-Yu Dong[2,3], Yan Chen[1,4]*

[1]Department of Physics, Fudan University , Shanghai

[2] Department of Physics and Institute for Quantum Information and Matter, California Institute of Technology, Pasadena, California 91125, USA

[3] Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139

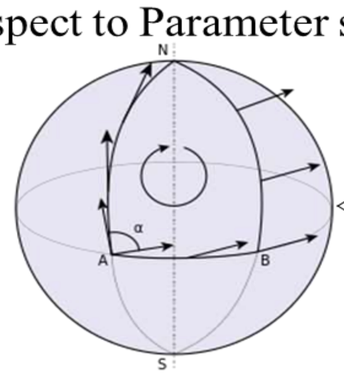
[4]Shanghai Branch, Hefei National Laboratory, Shanghai 201315, P.R. China

Abstract

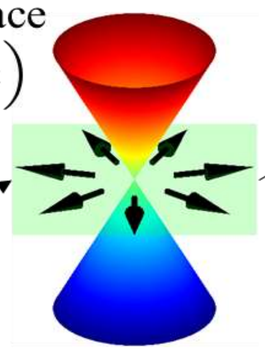
We explore numerically the intricate interplay between Berry phases in both real and momentum spaces within itinerant magnets. This interplay manifests as an emergent spin-orbit coupling, where charge carriers occupying a Berry-curved band generate an orbital magnetization, inducing a pseudo-magnetic field originating in chiral spin textures. Using density-matrix-renormalization-group techniques, we demonstrate that switching on a band Berry curvature in a metallic ferromagnetic phase results in chiral magnetic textures. Furthermore, employing a two-leg strip geometry, we establish a connection between charge and spin chirality, further supporting this emergent spin-orbit interaction.

Interplay between r-space and k-space Berry phase

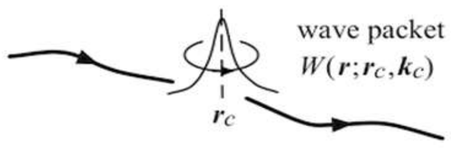
Quantum state's adiabatic cyclotronic evolution with respect to Parameter space



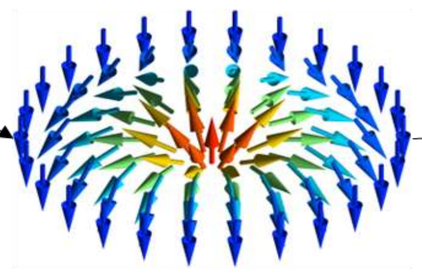
Momentum space $\Omega(\vec{k})$

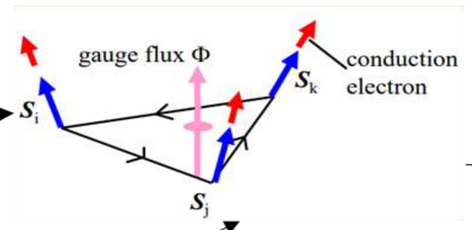


Orbital magnetization $\mathcal{M}$



Real space $\Omega(\vec{r})$

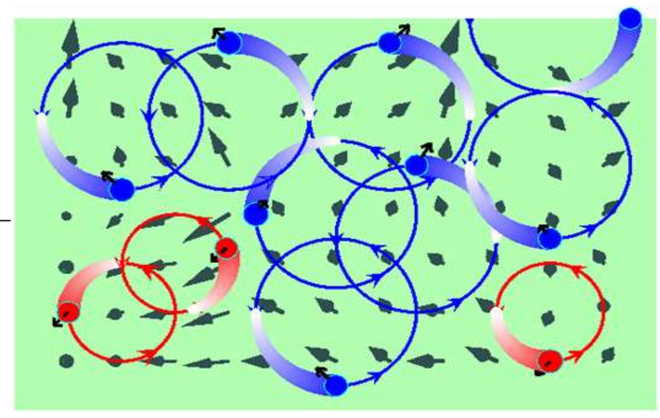




Coulomb Interaction

Stoner FM instability

Emergent SOI driven Spin Chirality

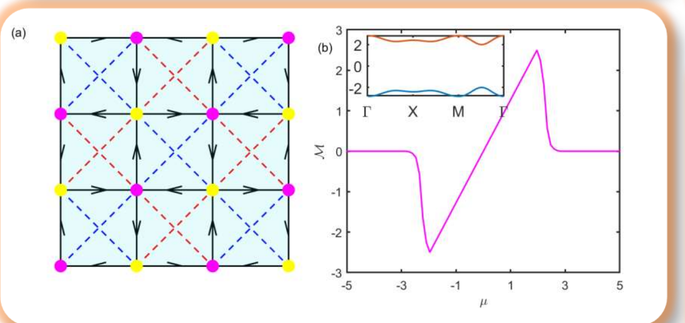


$$\mathcal{H}_{SOI} = -(\mathcal{M}_\uparrow - \mathcal{M}_\downarrow)B,$$

$$B = \frac{\phi_0}{4\pi}\boldsymbol{S}\cdot(\partial_x\boldsymbol{S}\times\partial_y\boldsymbol{S}), \phi_0 = \frac{hc}{e}$$

Minimal Lattice Model

$$\mathcal{H} = -t_1\sum_{\langle jm\rangle,\sigma}\left(e^{i\phi\delta_1^{jm}}c_{j\sigma}^\dagger c_{m\sigma} + H.c.\right) - t_2\sum_{\langle\langle jm\rangle\rangle,\sigma}(\delta_2^{jm}c_{j\sigma}^\dagger c_{m\sigma} + H.c.) + U\sum_j n_{j\uparrow}n_{j\downarrow}$$

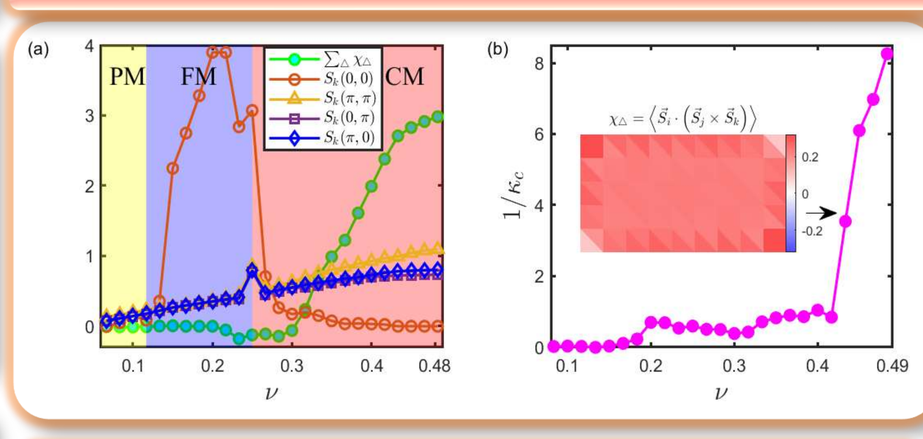


$$\mathcal{M} = \int_{\varepsilon\le\mu}\frac{d\boldsymbol{k}}{(2\pi)^d}\left(\boldsymbol{m}_n(\boldsymbol{k}) + \frac{e}{\hbar}[\mu-\varepsilon(\boldsymbol{k})]\Omega_n(\boldsymbol{k})\right)$$

$$\boldsymbol{m}_n(\boldsymbol{k}) = \frac{-ie}{2\hbar}\langle\nabla_{\boldsymbol{k}}u_{n\boldsymbol{k}}|\left[\hat{H}-\varepsilon_{n\boldsymbol{k}}^0\right]|\nabla_{\boldsymbol{k}}u_{n\boldsymbol{k}}\rangle$$

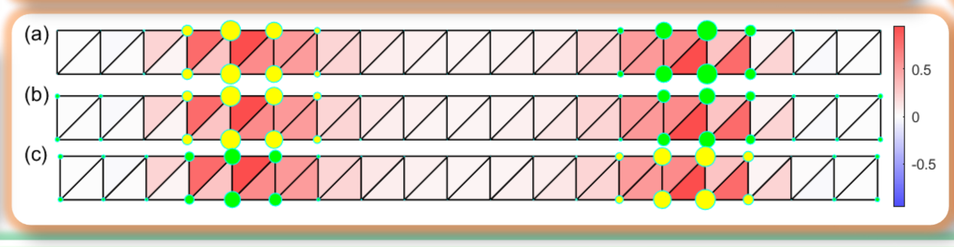
Charge density and local spin polarization modulated with spin chirality

Flat band FM to Chiral metallic Phase

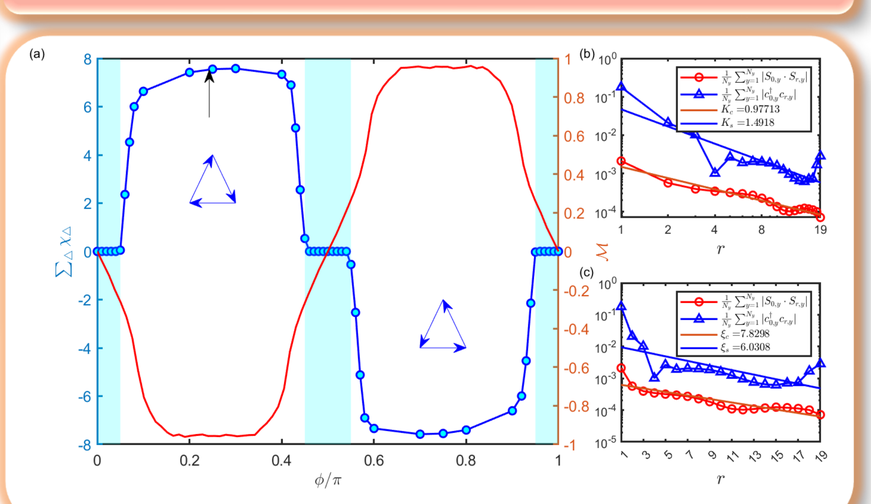


- Flat band FM evolve into a conductivite Chiral spin textured metal with increasing filling number
- Inverse charge compressibility exhibits a peak when approaching half-filling.

$$\kappa_c^{-1} \approx \frac{N_e^2}{N_s^2}[E(N_e+\delta N_e)+E(N_e-\delta N_e)-2E(N_e)]/\delta N_e^2$$



Chiral spin textured metal based on Nagaoka FM



- OM equal to zero at symmetric points, so does scalar spin chirality.
- Zero spin chirality plateau arising from SOI energy gain not beat spin stiffness energy cost

$$S_i^z = \langle n_i^\uparrow - n_i^\downarrow\rangle$$

$$\delta n_i^\uparrow = \langle n_i^\uparrow - \nu\rangle$$

$$\delta n_i^\downarrow = \langle n_i^\downarrow - \nu\rangle$$

$$\delta n_\sigma(\boldsymbol{r}) = \sigma B(\boldsymbol{r})\oint_{k_F^\sigma}\frac{m_\sigma(\boldsymbol{k})d\boldsymbol{k}}{(2\pi^2)v_F^\sigma(\boldsymbol{k})}$$

References

[1] S.Yang, Z.Dong, and Yan. Chen, Chiral spin textures driven by emergent spin-orbit interaction: a numerical study, arXiv:2404.00706.

[2] Z.Dong, and L. Levitov, Chiral stoner magnetism in dirac bands, arXiv:2208.02051

[3] Z.Dong, O.Ogunnaike, and L. Levitov, Collective excitations in chiral stoner magnets, Phys. Rev. Lett. 130,206701(2023)