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Editor's Focus

Weyl monopoles dance with the spin waves

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In a Weyl semimetal (WSM), the conduction and valence bands cross each other near the Fermi energy, and the crossing points, called Weyl points, exhibit a monopole-like distribution of the Berry curvature. The Berry curvature is a fictitious magnetic field in the momentum-space and induces the anomalous velocity to the real-space electron motion. Therefore, Weyl monopoles play essential roles in the charge transport, for example, the anomalous Hall effect (AHE). The anomalous Hall conductivity (AHC) is nearly proportional to the distance between the Weyl point pairs with opposite chirality. The magnetic order and spin structure sensitively modify Weyl point positions and energies.

Recently, $Co_3Sn_2S_2$ has been extensively studied as a prototype of magnetic WSM [1] with increasing attention. This compound hosts Weyl points at only 60 meV above the Fermi energy and by a low charge carrier density. The wide separation of Weyl points induces a giant AHE with the AHC ~1130 Ω^{-1} cm^{-1} and the Hall angle up to 20% [1]. The existence of Weyl points in the bulk and Fermi arc states on the surface were verified by surface spectroscopic probes [1]. The WSM also exhibits other topology-induced phenomena such as surface Fermi arcs [1], the anomalous Nernst effect (ANE) [2] and possible chiral edge states [3]. Because Co atoms form a magnetic Kagome lattice, this compound also provokes interests in flat-bands and the frustrated physics [4]. It is even studied to catalyze the water splitting [5].

Theoretically, the Weyl points also influence the spin dynamics in a magnetic WSM. The spin orientation sensitively tunes the band structure and subsequently manipulates the positions and energies of Weyl points (as illustrated in Figure 1), leading to modified AHE. At the finite temperature, the collective motion of magnetic moments forms spin waves. One can imagine that spin waves can modify the static scenario of Weyl points and the AHE. Because of the strong coupling between the spin and motion in Weyl materials, the modified AHE shakes the spin waves, too. Such effect establishes an intimate relationship between the AHC and spin dynamics, where both the spin stiffness and the spin wave gap are modified away from the behaviors of the conventional ferromagnetic spin wave [6].

Very recently, Liu et al. [7] presented a comprehensive neutron scattering study on high-quality single-crystals of $Co_3Sn_2S_2$. By mapping the dispersions of spin waves up to 18 meV both in plane and out of plane, Liu et al. surprisingly revealed three-dimensional spin waves in this quasi-two-dimensional material, although the exchange couplings are not very strong due to its itinerant nature. They also found a full spin wave gap below 2.3 meV at T=4 K, much larger than the magnetic anisotropy energy (about 0.6 meV). By tracing the temperature evolution of the spin wave gap below the Curie temperature, the impact of the AHE on the spin dynamics was clearly evidenced. Similar experiments were performed in a WSM candidate, yet to be confirmed, $SrRuO_3$ [8]. In this work, Liu et al. unambiguously demonstrated the interplay between the low-energy spin dynamics and Weyl monopoles. Also, they observed substantial spin stiffness that is relevant to Weyl points.

The spin dynamics of magnetic WSM studied in this work

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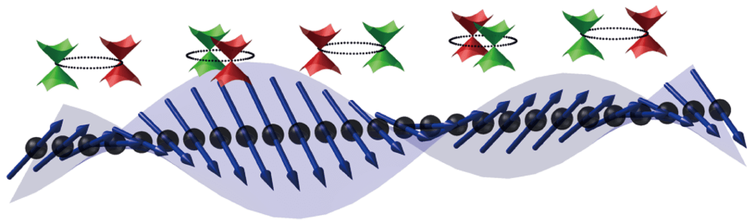

Figure 1 (Color online) Schematics of the interplay between spin waves and Weyl points.

may provide insights into many new directions. For example, from the ferromagnetic state to the paramagnetic state, the spin dynamics vary dramatically. The ANE, which is the transverse thermoelectric coupling induced by the Berry curvature near the magnetic transition, should diminish when the spin waves become gapless. However, the ANE exhibits an unexplained large peak before entering the paramagnetic phase, as observed in $Co_3Sn_2S_2$ by previous experiments [2]. This is different from the AHE behavior. The intriguing spin dynamics may account for the ANE behavior, which calls for more studies. As the topological band structure can be tuned by chemical doping or external pressure, the AHE may be improved further, leading to a promising potential for quantum technology applications [9]. The information from spin dynamics will be a helpful guide for such explorations. In addition, the Weyl-spin interaction may deserve further investigations with emerging magnetic imaging techniques, for example, the NV center magnetometry [10], which can provide the real-space information of spin dynamics.

1 E. Liu, Y. Sun, N. Kumar, L. Muechler, A. Sun, L. Jiao, S. Y. Yang, D. Liu, A. Liang, Q. Xu, J. Kroder, V. Süß, H. Borrmann, C. Shekhar, Z. Wang, C. Xi, W. Wang, W. Schnelle, S. Wirth, Y. Chen, S. T. B. Goennenwein, and C. Felser, Nat. Phys. **14**, 1125 (2018), arXiv: 1712.06722; Q. Wang, Y. Xu, R. Lou, Z. Liu, M. Li, Y. Huang, D. Shen, H. Weng, S. Wang, and H. Lei, Nat. Commun. **9**, 3681 (2018), arXiv: 1712.09947; D. F. Liu, A. J. Liang, E. K. Liu, Q. N. Xu, Y. W. Li, C. Chen, D. Pei, W. J. Shi, S. K. Mo, P. Dudin, T. Kim, C. Cacho, G. Li, Y. Sun, L. X. Yang, Z. K. Liu, S. S. P. Parkin, C. Felser, and Y. L. Chen, Science **365**, 1282 (2019), arXiv: 1909.09580; N. Morali, R. Batabyal, P. K. Nag, E. Liu, Q. Xu, Y. Sun, B. Yan, C. Felser, N. Avraham, and H. Beidenkopf, Science **365**, 1286 (2019), arXiv: 1903.00509; H. M. Weng, Sci. China-Phys. Mech. Astron. **62**, 127031 (2019).

2 L. Ding, J. Koo, L. Xu, X. Li, X. Lu, L. Zhao, Q. Wang, Q. Yin, H. Lei, B. Yan, Z. Zhu, and K. Behnia, Phys. Rev. X **9**, 041061 (2019), arXiv: 1907.05565; S. N. Guin, P. Vir, Y. Zhang, N. Kumar, S. J. Watzman, C. Fu, E. Liu, K. Manna, W. Schnelle, J. Gooth, C. Shekhar, Y. Sun, and C. Felser, Adv. Mater. **31**, 1806622 (2019).

3 S. Howard, L. Jiao, Z. Wang, P. Vir, C. Shekhar, C. Felser, T. Hughes, and V. Madhavan, arXiv: 1910.11205.

4 J. X. Yin, S. S. Zhang, G. Chang, Q. Wang, S. S. Tsirkin, Z. Guguchia, B. Lian, H. Zhou, K. Jiang, I. Belopolski, N. Shumiya, D. Multer, M. Litskevich, T. A. Cochran, H. Lin, Z. Wang, T. Neupert, S. Jia, H. Lei, and M. Z. Hasan, Nat. Phys. **15**, 443 (2019), arXiv: 1901.04822; E. Lachman, R. A. Murphy, N. Maksimovic, R. Kealhofer, S. Haley, R. D. McDonald, J. R. Long, and J. G. Analytis, Nat. Commun. **11**, 560 (2020), arXiv: 1907.06651.

5 G. Li, Q. Xu, W. Shi, C. Fu, L. Jiao, M. E. Kamminga, M. Yu, H. Tüysüz, N. Kumar, V. Süß, R. Saha, A. K. Srivastava, S. Wirth, G. Auffermann, J. Gooth, S. Parkin, Y. Sun, E. Liu, and C. Felser, Sci. Adv. **5**, eaaw9867 (2019), arXiv: 1908.08567.

6 M. Onoda, A. S. Mishchenko, and N. Nagaosa, J. Phys. Soc. Jpn. **77**, 013702 (2008).

7 C. Liu, J. L. Shen, J. C. Gao, C. J. Yi, D. Liu, T. Xie, L. Yang, S. Danilkin, G. C. Deng, W. H. Wang, S. L. Li, Y. G. Shi, H. M. Weng, E. K. Liu, and H. Q. Luo, Sci. China-Phys. Mech. Astron. **64**, 217062 (2021).

8 S. Itoh, Y. Endoh, T. Yokoo, S. Ibuka, J. G. Park, Y. Kaneko, K. S. Takahashi, Y. Tokura, and N. Nagaosa, Nat. Commun. **7**, 11788 (2016); K. Jenni, S. Kunkemöller, D. Brüning, T. Lorenz, Y. Sidis, A. Schneidewind, A. A. Nugroho, A. Rosch, D. I. Khomskii, and M. Braden, Phys. Rev. Lett. **123**, 017202 (2019), arXiv: 1902.04036.

9 Z. Guguchia, J. A. T. Verezhak, D. J. Gawryluk, S. S. Tsirkin, J. X. Yin, I. Belopolski, H. Zhou, G. Simutis, S. S. Zhang, T. A. Cochran, G. Chang, E. Pomjakushina, L. Keller, Z. Skrzeczkowska, Q. Wang, H. C. Lei, R. Khasanov, A. Amato, S. Jia, T. Neupert, H. Luetkens, and M. Z. Hasan, Nat. Commun. **11**, 559 (2020); J. Shen, Q. S. Yao, Q. Q. Zeng, H. Y. Sun, X. K. Xi, G. H. Wu, W. H. Wang, Q. H. Liu, and E. K. Liu, arXiv: 2002.03917; H. Zhou, G. Chang, G. Wang, X. Gui, X. Xu, J. X. Yin, Z. Guguchia, S. S. Zhang, T. R. Chang, H. Lin, W. Xie, M. Z. Hasan, and S. Jia, Phys. Rev. B **101**, 125121 (2020), arXiv: 2003.02412.

10 J. R. Maze, P. L. Stanwix, J. S. Hodges, S. Hong, J. M. Taylor, P. Cappellaro, L. Jiang, M. V. G. Dutt, E. Togan, A. S. Zibrov, A. Yacoby, R. L. Walsworth, and M. D. Lukin, Nature **455**, 644 (2008); G. Balasubramanian, I. Y. Chan, R. Kolesov, M. Al-Hmoud, J. Tisler, C. Shin, C. Kim, A. Wojcik, P. R. Hemmer, A. Krueger, T. Hanke, A. Leitenstorfer, R. Bratschitsch, F. Jelezko, and J. Wrachtrup, Nature **455**, 648 (2008).