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Topological magnon insulator with Dzyaloshinskii–Moriya interaction under the irradiation of light*

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The topological magnon insulator on a honeycomb lattice with Dzyaloshinskii–Moriya interaction (DMI) is studied under the application of a circularly polarized light. At the high-frequency regime, the effective tight-binding model is obtained based on Brillouin–Wigner theory. Then, we study the corresponding Berry curvature and Chern number. In the Dirac model, the interplay between a light-induced handedness-dependent effective DMI and intrinsic DMI is discussed.

Keywords: magnon, light, Brillouin–Wigner theory, Dzyaloshinskii–Moriya

PACS: 85.75.–d, 78.67.–n, 75.30.–m **DOI:** 10.1088/1674-1056/28/7/078503

1. Introduction

A topological insulator is a material that has a bulk band gap like an ordinary insulator but whose surface contains conducting states.[1,2] The search for topological states of quantum matter is one of the hottest topics in condensed matter physics. The topologically protected edge states is not unique to electronic systems. A growing number of studies investigate the possibility of topological properties on magnons in two-dimensional (2D) honeycomb systems[3–12] due to their similarity to electrons in graphene.[13,14] The ferromagnetic spins on a 2D honeycomb lattice can be topologically nontrivial when a proper nearest neighbor exchange exists.[3] In Ref. [4], the authors investigated the properties of magnon edge states in a ferromagnetic honeycomb spin lattice with a Dzyaloshinskii–Moriya interaction (DMI). Beginning from an isotropic Heisenberg model of localized spin moments in a honeycomb lattice, Fransson *et al.*[5] addressed the possibility of emerging Dirac magnons. Ferreiros[7] *et al.* studied the influence of lattice deformations on the magnon physics of a honeycomb ferromagnet when a DMI is considered. Owerre[8] showed that the magnon Hall effect is realizable in a two-band model on the honeycomb lattice, and studied the thermal Hall conductivity. Employing the Landau–Lifshitz–Gilbert phenomenology, bulk and edge spin transport in topological magnon insulators have been studied.[9] The spin Nernst effect of magnons in a honeycomb antiferromagnet in the presence of a DMI has been demonstrated.[10,11]

Another direction that the study of topological phases has taken in recent years is manipulating the topological and transport properties of quantum systems under the influence of a periodic drive.[15–17] Changes in the band structure from a nontopological band structure to a topological one can occur. In cold atom systems, periodic changes in the laser fields establish an optical lattice potential.[18,19] In solid state systems, periodically modulated quantum systems can be effectively described by a static Hamiltonian. Therefore, magnon systems deserve consideration. In this work, we study the magnon on a honeycomb lattice with a DMI under the irradiation of light.[20–24] We study the effects of the interplay between the DMI and light.

The rest of this paper is organized as follows. In Section 2, we present the tight-binding magnon model on the honeycomb lattice. Based on the Brillouin–Wigner theory, we obtain the effective tight-binding Hamiltonian with a circularly polarized light. In Section 3, the Berry curvature and Chern number of the system are presented. In Section 3, the corresponding low-energy Dirac model is studied. Our conclusions are given in Section 5.

2. Model

We consider a ferromagnetic model on a honeycomb lattice. The corresponding Hamiltonian is

$$H = -J\sum_{\langle ij\rangle} \boldsymbol{S}_i \cdot \boldsymbol{S}_j + D\sum_{\langle\langle ij\rangle\rangle} \nu_{ij}\hat{z}\cdot \boldsymbol{S}_i \times \boldsymbol{S}_j, \tag{1}$$

where $\boldsymbol{S}_i = (S_i^x, S_i^y)$ is the spin moment at site i. $J > 0$ is the nearest neighbor ferromagnetic exchange coupling. The second term is the DMI between the second nearest neighbors. The constants $\nu_{ij} = \boldsymbol{d}_i \times \boldsymbol{d}_j/|\boldsymbol{d}_i|/|\boldsymbol{d}_j|$ with the vectors $\boldsymbol{d}_i$ connecting site i to its second nearest neighbor j is shown in Fig. 1.

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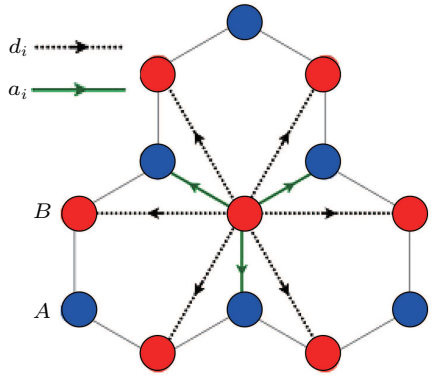


Fig. 1. The honeycomb lattice structure, with the nearest neighbor and the second nearest neighbors labeled by a_i and d_i, respectively.

Using Holstein–Primakoff transformation $S_i^+ = S_i^x + S_i^y = c_i\sqrt{2S-n_i}$, $S_i^- = S_i^x - S_i^y = c_i^\dagger\sqrt{2S-n_i}$, and $S_i^z = S - n_i$ with $n_i = c_i^\dagger c_i$, we obtain

$$\begin{aligned} H &= 3JS\sum_i c_i^\dagger c_i - JS\sum_{\langle ij\rangle}\left[c_i^\dagger c_j + \text{h.c.}\right] \\ &\quad - DS\sum_{\langle\langle ij\rangle\rangle} i\nu_{ij}\left[c_i^\dagger c_j + \text{h.c.}\right], \end{aligned} \tag{2}$$

where c_i and $c_i^\dagger$ are magnon operators, and $i, j = A, B$ label the two sublattices of the honeycomb lattice denoted by different colors in Fig. 1. The Hamiltonian in the momentum space can be written as $H = \sum_{\boldsymbol{k}} \psi_{\boldsymbol{k}}^\dagger H(\boldsymbol{k})\psi_{\boldsymbol{k}}$, where $\psi_{\boldsymbol{k}}^\dagger = [c_{A\boldsymbol{k}}^\dagger, c_{B\boldsymbol{k}}^\dagger]$ and

$$H(\boldsymbol{k}) = \begin{pmatrix} 3JS + \Delta(\boldsymbol{k}) & f(\boldsymbol{k}) \\ f(-\boldsymbol{k}) & 3JS - \Delta(\boldsymbol{k}) \end{pmatrix}, \tag{3}$$

where

$$f(\boldsymbol{k}) = JS\sum_i e^{i\boldsymbol{k}\cdot\boldsymbol{a}_i} = JS\left[2e^{i\frac{k_y}{2\sqrt{3}}}\cos\frac{k_x}{2} + e^{-i\frac{k_y}{\sqrt{3}}}\right], \tag{4}$$

$$\Delta(\boldsymbol{k}) = \sum_i e^{i\boldsymbol{k}\cdot\boldsymbol{d}_i} = 2DS\left[\sin k_x - 2\sin\frac{k_x}{2}\cos\frac{\sqrt{3}k_y}{2}\right], \tag{5}$$

and where $\boldsymbol{a}_{1,2} = (\pm 1, 1/\sqrt{3})/2$, $\boldsymbol{a}_3 = (0,-1)/\sqrt{3}$, $\boldsymbol{d}_{1,3} = \pm(1,\sqrt{3})/2$, $\boldsymbol{d}_{2,5} = \pm(-1,\sqrt{3})/2$, and $\boldsymbol{d}_{3,6} = \pm(1,0)$. We have set the lattice constant as 1 throughout the paper. In the absence of DMI, the magnon bands are massless at the two Dirac points $K = (4\pi/3, 0)$ and $K' = (-4\pi/3, 0)$.

Next, we consider the effect of the circularly polarized light represented by the time-dependent vector potential

$$\boldsymbol{A}(t) = A(\sin\omega t, \cos\omega t), \tag{6}$$

where $A = E_0/\omega$, and E_0 and ω are the field strength and frequency, respectively. Then, the response of the light-illuminated system can be obtained by substituting $\boldsymbol{k}$ with $\boldsymbol{k} + e\boldsymbol{A}(t)$. Based on the Brillouin–Wigner theory,[25,26] we can write the effective Hamiltonian as

$$H_{\text{eff}} = H_0 + \sum_n \frac{[H_{-n}, H_n]}{n\omega}, \tag{7}$$

where $H_n = \frac{1}{T}\int_{-T/2}^{T/2} H(t)e^{-in\omega t}$. The second term represents the process of including the emission and absorption of the n-photon in the off-resonant light. In the off-resonant condition where the light does not cause any transition, one photon absorption and emission are enough for virtual process. Straightforward calculations show us that

$$H_{\text{eff}} = \widetilde{H}_0 + \frac{1}{\omega}\sum_{i=x,y,z} H_i^A \sigma^i, \tag{8}$$

where $\widetilde{H}_0$ is equal to the bare Hamiltonian in the absence of light $H(\boldsymbol{k})$ in Eq. (3) except for the constant term with renormalization of the parameters: $J = JJ_0(\widetilde{A})$ and $D = DJ_0(\widetilde{A})$. $\widetilde{A} = eE_0a/\sqrt{3}\hbar\omega$, and $J_n(x)$ denotes the n-th Bessel function.

In addition,

$$H_z^A = -4D\sum_{n=1}^{\infty}\frac{J_n^2(\widetilde{A})\sin(\frac{2n\pi}{3})}{n}\sum_{j=1}^{3}\sin\boldsymbol{k}\cdot\boldsymbol{\gamma}_j, \tag{9}$$

where $\boldsymbol{\gamma}_1 = \boldsymbol{a}_1 - \boldsymbol{a}_3$, $\boldsymbol{\gamma}_2 = \boldsymbol{a}_2 - \boldsymbol{a}_1$, and $\boldsymbol{\gamma}_3 = \boldsymbol{a}_3 - \boldsymbol{a}_2$, and

$$H_x^A - iH_y^A = \sum_{n=1}^{\infty}\frac{2g_n^1 g_{-n}^2 - 2g_{-n}^1 g_n^2}{n}, \tag{10}$$

$$g_n^1 = JJ_n(\widetilde{A})\sum_{j=1}^{3} e^{-in\frac{\pi}{6}+i(j-1)\frac{4\pi}{3}} e^{i\boldsymbol{k}\cdot\boldsymbol{a}_j}, \tag{11}$$

$$g_n^2 = iDJ_n(\widetilde{A})\left[e^{i(ak_x - n\pi)} - 2e^{i\frac{a}{2}k_x}\cos\left(\frac{\sqrt{3}}{2}ak_y - n\frac{\pi}{3}\right)\right]. \tag{12}$$

In Fig. 2(a), we find that finite DMI opens a gap, thereby endowing the magnon bands with a nontrivial topology. Based on Eq. (8), we see that the effect of circularly polarized light can result in a gapped system. The interplay between the DMI and light can induce closing and reopening of the band gap. In Fig. 2(b), we show that the critical points where the interplay makes the energy gap are closed.

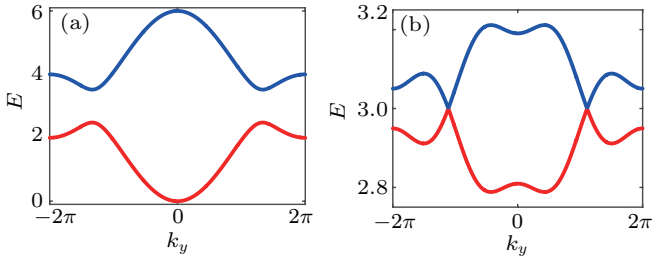


Fig. 2. Bulk magnon bands for momenta in the y direction for $D = 0.1J$ when (a) $\widetilde{A} = 0$ and (b) $\widetilde{A}_{\text{critical}} \approx 2.5J$.

3. Berry curvature and Chern number

The Berry curvature for the n-th magnon band can be calculated from

$$\Omega_n(\boldsymbol{k}) = -\sum_{n'\neq n}\frac{2\text{Im}\langle u_{n\boldsymbol{k}}|\hat{v}_x|u_{n'\boldsymbol{k}}\rangle\langle u_{n'\boldsymbol{k}}|\hat{v}_y|u_{n\boldsymbol{k}}\rangle}{(E_{n'} - E_n)^2}. \tag{13}$$

The summation is over all occupied bands below the bulk gap, and $\hat{v}_{x(y)}$ is the velocity operator along the $x(y)$ direction. E_n is the eigenvalue of the system (Eq. (8)). In Fig. 3, we show the

Berry curvature of the lower band at $D = 0.1J$ for the varying light parameter $\widetilde{A}$. We can see that the Berry curvatures change with $\widetilde{A}$. We find that the Berry curvature increases as $\widetilde{A}$ increases for $\widetilde{A} < \widetilde{A}_{\text{critical}}$ while the reverse occurs for $\widetilde{A} > \widetilde{A}_{\text{critical}}$. The associated Chern number is defined as

$$\mathcal{C} = \frac{1}{2\pi}\int \mathrm{d}^2 k \Omega^z(\boldsymbol{k}), \tag{14}$$

where the integral is over the first Brillouin zone. Consequently, the system changes from one topological magnon insulator with Chern number 1 to another one with Chern number -1. In other words, a light intensity field can lead to a topological phase transition in a topological magnon insulator.

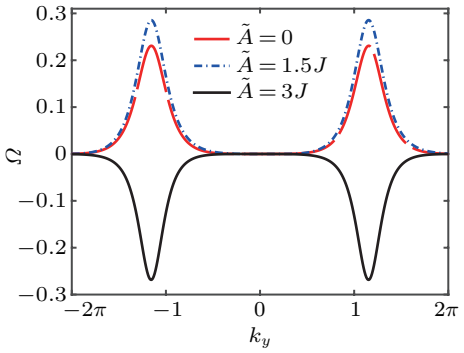


Fig. 3. Berry curvature of the lower magnon band for $D = 0.1J$.

4. Low-energy Dirac theory

To better understand the topological properties, we present a theoretical analysis based on an effective $k\cdot p$ Hamiltonian. Expanding this Hamiltonian around the Dirac points to $\delta\boldsymbol{k}$, we obtain the effective Dirac Hamiltonian as

$$H_\eta = t(\eta\delta k_x\sigma_x - \delta k_y\sigma_y) + \eta\Delta_{\text{dm}}\sigma^z, \tag{15}$$

where $\eta = \pm 1$ corresponds to the two Dirac points, $\sigma_{x,y,z}$ are the Pauli matrices of the sublattice pseudospin, $t = \frac{\sqrt{3}}{2}JS$, and $\Delta_{\text{dm}} = 3\sqrt{3}DS$. The system can be described by a static Hamiltonian in the high-frequency regime.[15,27] Then, the static time-independent Hamiltonian is written as

$$H_\eta^{\text{eff}} = t(\eta\delta k_x\sigma_x - \delta k_y\sigma_y) + \eta\left[\Delta_{\text{dm}} - \frac{A^2t^2}{\hbar\omega}\right]\sigma^z. \tag{16}$$

The band dispersion relationship of the above Hamiltonian is

$$E_\pm = \pm\sqrt{t^2\delta k^2 + \Delta^2}, \tag{17}$$

and the the corresponding wave functions are

$$u_{+\boldsymbol{k}} = \left[\cos\frac{\theta}{2}, \sin\frac{\theta}{2}\mathrm{e}^{-\mathrm{i}\varphi}\right]^{\mathrm{T}}, \tag{18}$$

$$u_{-\boldsymbol{k}} = \left[\sin\frac{\theta}{2}, -\cos\frac{\theta}{2}\mathrm{e}^{-\mathrm{i}\varphi}\right]^{\mathrm{T}}, \tag{19}$$

where $\Delta = \Delta_{\text{dm}} - A^2t^2/\hbar\omega$, $\cos\theta = \Delta/\sqrt{t^2\delta k^2 + \Delta^2}$, and $\cos\varphi = \delta k_x/\delta k$. Based on Eq. (14), we obtain

$$\Omega^z = -\eta\frac{1}{2}\frac{t^2\left(\Delta_{\text{dm}} - \dfrac{A^2t^2}{\hbar\omega}\right)}{\left[t^2\delta k^2 + \left(\Delta_{\text{dm}} - \dfrac{A^2t^2}{\hbar\omega}\right)^2\right]^{3/2}}, \tag{20}$$

$$C = \frac{\Delta_{\text{dm}} - \dfrac{A^2t^2}{\hbar\omega}}{\left|\Delta_{\text{dm}} - \dfrac{A^2t^2}{\hbar\omega}\right|}. \tag{21}$$

One sees that an extra light-induced term $A^2t^2/\hbar\omega$ is introduced, and its sign depends on the polarization of light. This new term is clearly different from the intrinsic DMI term, and it can be defined as the light-induced effective DMI. The overall value of the DMI will decrease (increase) if the DMI term and the polarization of light have the same (different) sign. For the same sign, the critical point is defined at $\Delta_{\text{dm}} - A^2t^2/\hbar\omega$ where the overall DMI vanishes and the band gap closes. For example, when increasing the circularly polarized light intensity, figure 2 shows a band gap closing. The Dirac theory is consistent with the results from tight-binding theory.

The direct correspondence between the Chern number and the Hall conductance for 2D system is characterized by $\sigma_{xy} = Ce^2/h$. The band gap ($\Delta_{\text{dm}} - A^2t^2/\hbar\omega$) is closed and reopened for fixed Δ_{dm} when varying A, and the direction of the Hall current is changed. Therefore, the direction of the Hall current can be controlled by illuminating with light due to the fact that they lead to the change in sign of the Berry curvature of the valence band. It should be noted that in our paper, we only consider $\omega > 0$. When $\omega < 0$, $\Delta_{\text{dm}} - A^2t^2/\hbar\omega > 0$. The band will not close and reopen. The topological phase transition and change in direction of the Hall current will not occur.

5. Conclusion and summary

To conclude, we analyzed the topological properties of magnon in an insulator on a honeycomb lattice with DMI under the application of a circularly polarized light. We employed Brillouin–Wigner theory to obtain the tight-binding model with a circularly polarized light at the high-frequency regime. We found that the light can induce the closing and reopening of the band gap. The study about the corresponding Berry curvature and Chern number confirmed the light-induced topological phase transition. We obtained the low-energy Dirac model to better know the topological properties. The topological phase transition was light-induced handedness-dependent. The effective DMI and intrinsic DMI were responsible for the topological phase transition.

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