Topological magnons in a one-dimensional itinerant flatband ferromagnet

Xiao-Fei Su[1,2], Zhao-Long Gu[1], Zhao-Yang Dong[1], Jian-Xin Li[1,3*]

[1]Department of Physics, Nanjing University, Nanjing, China 210093

[2]School of Physics and Electronic Information, Huaibei Normal University, Huaibei, China 235000

[3]Collaborative Innovation Center of Advanced Microstructures, Nanjing, China 210093

Abstract Different from previous scenarios that topological magnons emerge in local spin models, we propose an alternative that itinerant electron magnets can host topological magnons. A one-dimensional Tasaki model with a flatband is considered as the prototype. This model can be viewed as a quarter-filled periodic Anderson model with impurities located in between and hybridizing with the nearest-neighbor conducting electrons, together with a Hubbard repulsion for these electrons. By increasing the Hubbard interaction, the gap between the acoustic and optical magnons closes and reopens while the Berry phase of the acoustic band changes from 0 to π, leading to the occurrence of a topological transition. After this transition, there always exist in-gap edge magnonic modes, which is consistent with the bulk-edge correspondence. The Hubbard interaction-driven transition reveals a new mechanism to realize nontrivial magnon bands.

Introduction

Band structure with nontrivial topology has been one of the most active fields in condensed matter physics since the discovery of topological insulators. Although pioneering works focused on fermionic bands, the underlying concepts, such as Berry phase and Chern number, apply equally to systems that host bosonic ones. Magnons, the bosonic quanta of collective spin-1 excitations in a magnetically ordered system, also exhibit band structures in crystals. Recently, the search of topological magnons has attracted much attention [1, 2, 3]. However, all previous theoretical and experimental works are based on local spin models where the linear spin wave theory (LSWT) provides a comprehensive understanding and the Dzyaloshinskii-Moriya interaction is crucial to generate nontrivial magnonic bands. Besides the local spin magnetism, there exists another class of magnetism, the itinerant magnetism, for which the standard LSWT fails. Then, a natural question of fundamental interest follows: Can topological magnons emerge in itinerant magnets? If so, what is the mechanism? Here, we will investigate this with a one-dimensional interacting electronic model with a flatband as the prototype.

Model and method

The prototype is a one-dimensional Tasaki model [4]. As is illustrated in Fig. 1(a), the Hamiltonian reads

$$H = t\sum_{\langle ij\rangle_{AA}} c^\dagger_{iA}c_{jA} + H.c. + \lambda\sum_{\langle ij\rangle_{AB}} c^\dagger_{iA}c_{jB} + H.c. + \epsilon\sum_i c^\dagger_{iB}c_{iB} + U_s\sum_i n_{iA\uparrow}n_{iA\downarrow} + U_d\sum_i n_{iB\uparrow}n_{iB\downarrow} \quad (1)$$

When $\epsilon = \lambda^2/t - 2t$, the free part of the model possesses an exact flat electron band, which is separated from the upper band by a gap equal to λ^2/t, as shown in Fig. 1(b). Here, λ is taken to be larger than both U_s and U_d. Then the Hubbard interactions can be projected onto the flatband. As is well known, the ground state of a half-filled flat electron band with Hubbard interactions is an itinerant ferromagnet. Then, the creation of a spin-1 excitation with a center-of-mass momentum q from the fully spin-polarized ground state is just to choose a single particle state with momentum k_i, flip the electron's spin on it and move it onto another single particle state with momentum $k_j = k_i - q$, as illustrated in Fig.1(c). Thus, the total dimension of the Hilbert space of spin-1 excitations with a definite center-of-mass momentum is linear with respect to the system size N_q, which is in sharp contrast to the exponential dependence in the usual exact diagonalization method (UED). Therefore, a much larger system can be numerically accessed by this projected exact diagonalization (PED) method.

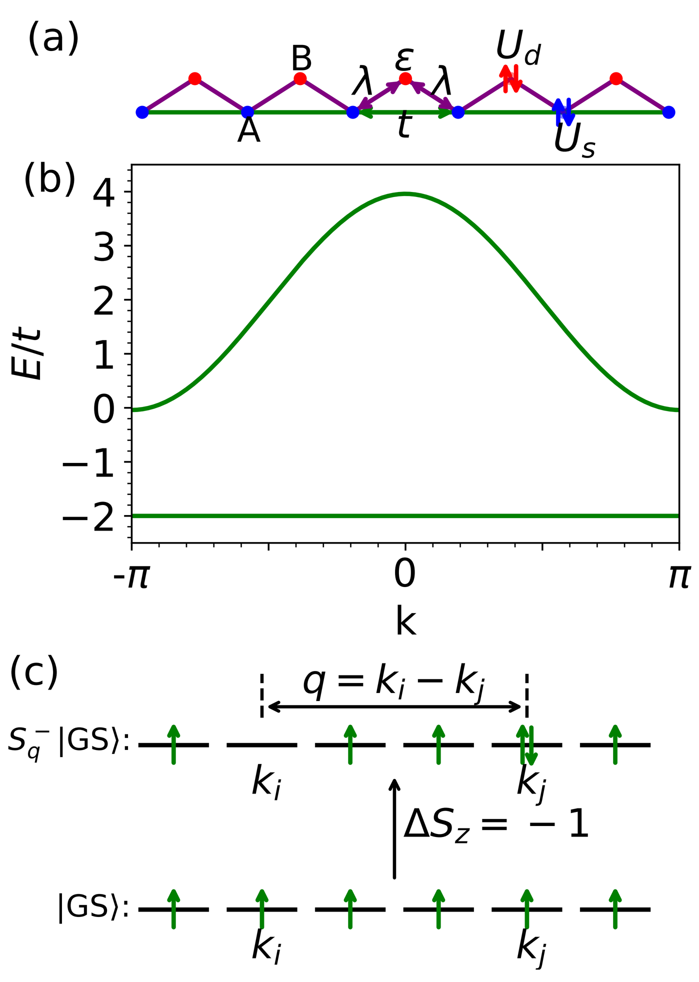

Fig. 1. (a) Schematic illustration of Eq. (1). (b) Band structure of the free part of Eq. (1) with $\epsilon = \lambda^2/t - 2t$. Here, $\lambda = 1.4t$. (c) Illustration of the creation of a spin-1 excitation with a center-of-mass momentum q on the ferromagnetic ground state in the PED method.

Topological itinerant magnons

Spectra of low-energy spin-1 excitations

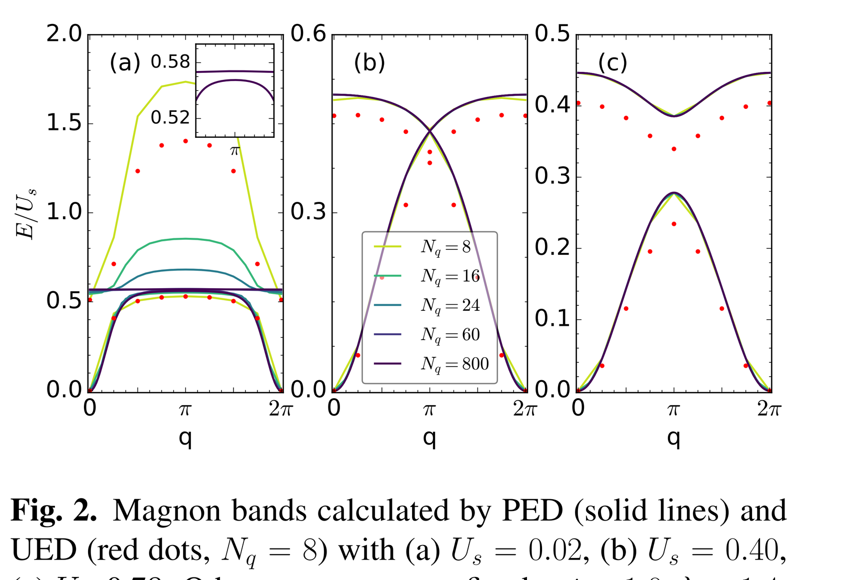

Fig. 2. Magnon bands calculated by PED (solid lines) and UED (red dots, $N_q = 8$) with (a) $U_s = 0.02$, (b) $U_s = 0.40$, (c) U_s=0.78. Other parameters are fixed at $t = 1.0$, $\lambda = 1.4$, $U_d = 1.0$. The inset in (a) shows the magnon bands calculated by PED with $N_q = 800$ around $q = \pi$, where the gap between the acoustic band and optical band is obvious.

- PED results and UED results agree with each other qualitatively, verifying the validity of the PED method.
- PED results converge when $N_q \geq 60$ although size dependence is obvious when $N_q < 60$ in the case of a small $U_s = 0.02$.
- There exist two branches of magnon bands, a gapless acoustic branch and a gapped optical branch.
- The gap between these two magnon bands closes and reopens with the increase of U_s, suggesting a kind of transition.
- This transition is not a traditional one because the ground state remains unchanged before and after it.

Berry phase and phase diagram

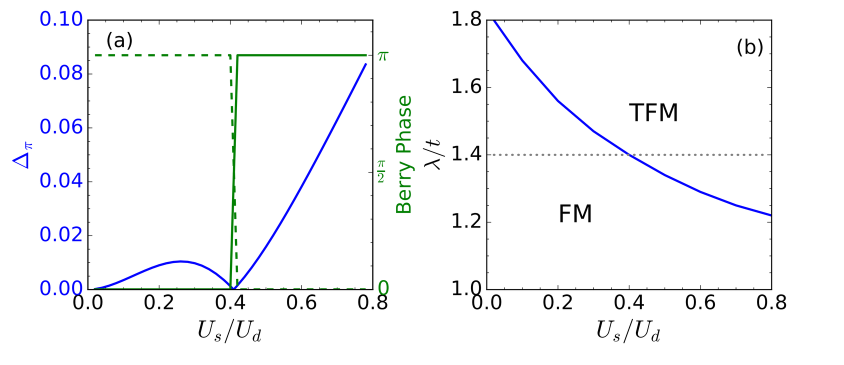

Fig. 3. (a) The blue line is the magnitude of the gap between the acoustic and optical band at $q = \pi$ with $N_q = 800$. The green solid/dashed line represents the corresponding Berry phase of the acoustic/optical band. Other parameters are fixed at $t = 1.0$, $\lambda = 1.4$, $U_d = 1.0$. (b) Phase diagram of Eq. (1). The dotted line marks the parameters used in Fig.3(a) and in Fig.4(a).

- With the gap closing and reopening, the Berry phase of the acoustic band changes from 0 to π while that of the optical band changes from π to 0.
- The Hubbard interaction induced transition is a topological transition.
- λ and U_s play a cooperative role in the generation of topological acoustic magnons because the onsite energy of the B sites $\epsilon = \lambda^2/t - 2t$ increases with the increase of λ, which results in transfers of electrons from the B site to A site, and thus enhances the effect of the Hubbard interactions on the A site.

Edge states

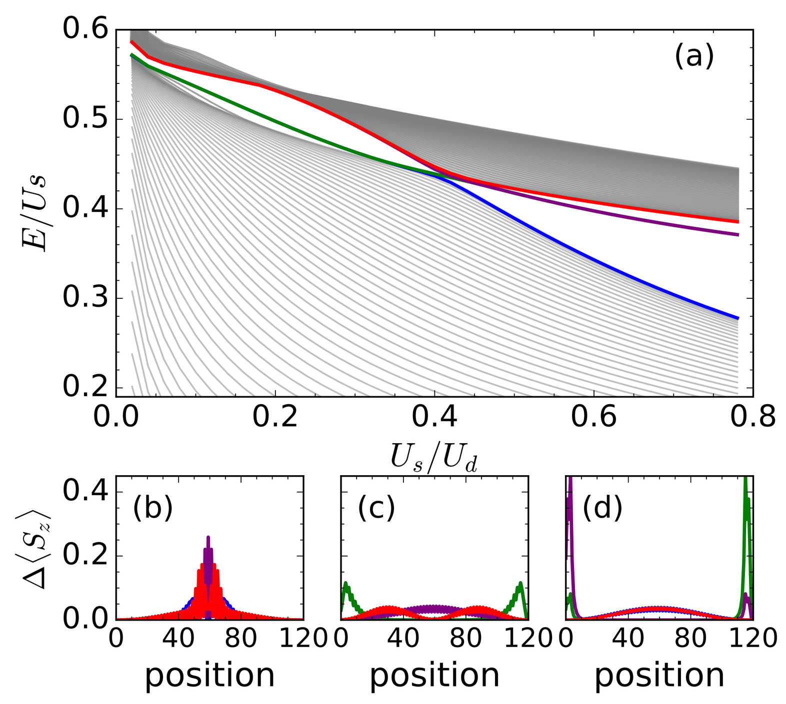

Fig. 4. At the top: (a) Magnon spectrum of Eq. (1) subject to open boundary conditions. At the bottom: Difference of the S_z profile between the in-gap or near-gap magnon states and ground state with (b) $U_s = 0.02$, (c) $U_s = 0.30$ and (d) $U_s = 0.78$. Other parameters are fixed at $t = 1.0$, $\lambda = 1.4$, $U_d = 1.0$.

- After the topological transition, there always exist in-gap magnonic edge modes, which is consistent with the bulk-edge correspondence.
- There seems to be in-gap magnonic edge modes before the topological transition when $U_s \sim 0.3$. However, these edge states disappear without closing the gap when U_s decreases to 0.02. Due to the finite size effect, whether these modes are intrinsic remains unclear.

Stability of topological itinerant magnons

Nonflatness

$$H_\Delta = \Delta\sum_i c^\dagger_{iB}c_{iB} \quad (2)$$

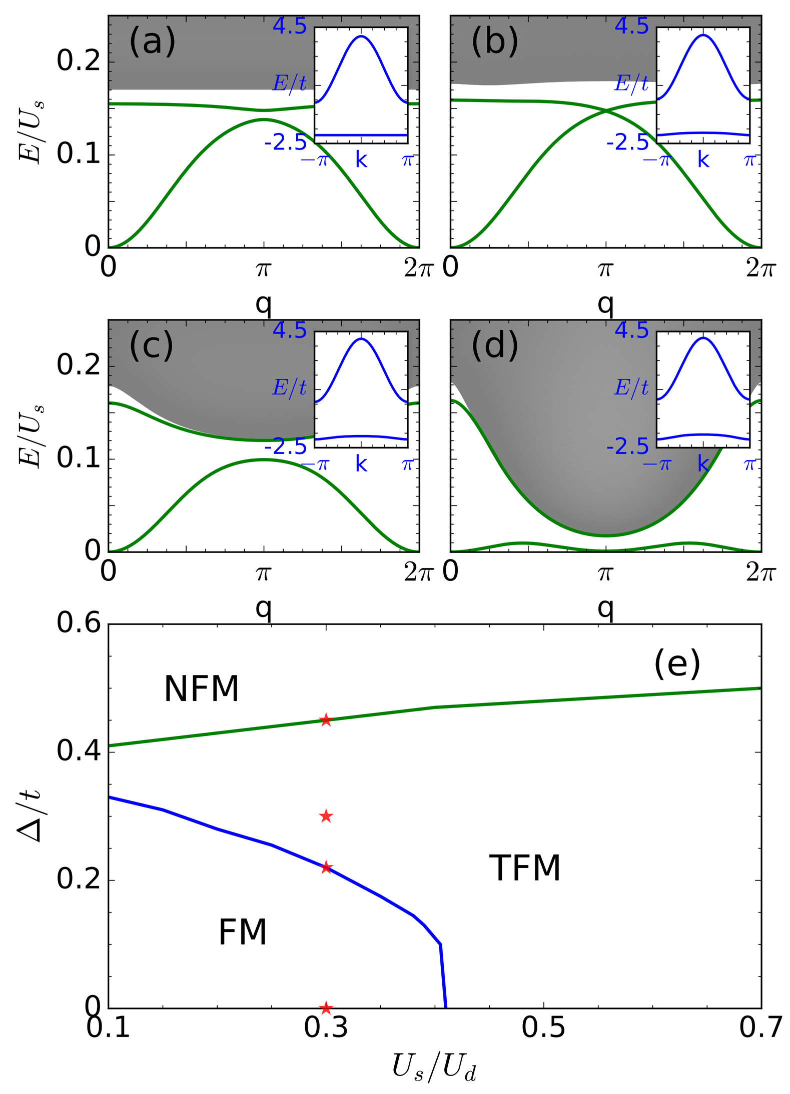

Fig. 5. (a)-(d) Spin-1 excitation spectra calculated by PED with $N_q = 800$ of Eq. (1) perturbed by Eq. (2) with (a) $U_s = 0.30$, $\Delta = 0$, (b) $U_s = 0.30$, $\Delta = 0.22$, (c) $U_s = 0.30$, $\Delta = 0.30$, (d) $U_s = 0.30$, $\Delta = 0.45$. The shaded area represents the Stoner continuum. Insets of (a)-(d) show the corresponding perturbed free electron bands. (e) The phase diagram in the Δ-U_s parameter space. NFM, FM and TFM represent nonferromagnetic phase, ferromagnetic magnons and topological ferromagnetic magnons, respectively. Red stars mark the parameters used in (a)-(d). Other parameters are fixed at $t = 1.0$, $\lambda = 1.4$, $U_d = 1.0$.

Nearest-neighbor interactions

$$H_V = V\sum_{\langle ij\rangle_{AB}} n^\dagger_{iA}n_{jB} \quad (3)$$

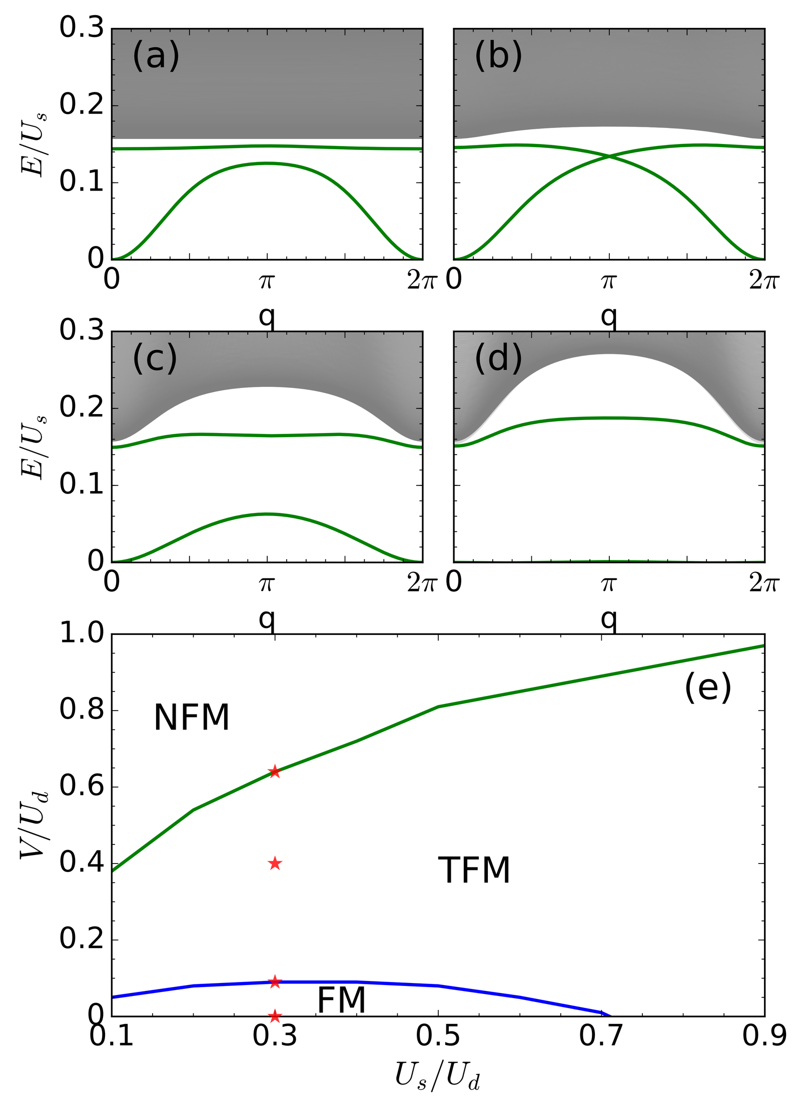

Fig. 6. (a)-(d) Spin-1 excitation spectra calculated by PED with $N_q = 800$ of Eq. (1) perturbed by Eq. (3) with (a) $U_s = 0.30$, $V = 0$, (b) $U_s = 0.30$, $V = 0.09$, (c) $U_s = 0.30$, $V = 0.40$, (d) $U_s = 0.30$, $V = 0.64$. The shaded area represents the Stoner continuum. (e) The phase diagram in the V-U_s parameter space. NFM, FM and TFM represents nonferromagnetic phase, ferromagnetic magnons and topological ferromagnetic magnons, respectively. Red stars mark the parameters used in (a)-(d). Other parameters are fixed at $t = 1.0$, $\lambda = 1.25$, $U_d = 1.0$.

Conclusions

We elaborate a new scenario that topological acoustic magnons can emerge from itinerant flatband ferromagnet, which is different from previous ones that topological magnons exists in local spin models. The prototype model is a one-dimensional flatband ferromagnet, which can be viewed as a quarter filled periodic Anderson model with impurities located at the center of the bonds and hybridizing with conducting electrons at their neighboring sites. Concentrating on the physics related to the flatband, we can project the model Hamiltonian onto the flat band and carry out the large-size calculation of spin-1 excitations based on the exact diagonalization method. We find a correlation-driven topological transition to realize nontrivial acoustic magnons, which is driven by the on-site Hubbard repulsion for conducting electrons.

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[*] jxli@nju.edu.cn

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