Spin dynamics of a magnetic Weyl semimetal Sr$_{1-x}$Mn$_{1-y}$Sb$_2$

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Dirac matters provide a platform for exploring the interplay of their carriers with other quantum phenomena. Sr$_{1-x}$Mn$_{1-y}$Sb$_2$ has been proposed to be a magnetic Weyl semimetal and provides an excellent platform to study the coupling between Weyl fermions and magnons. Here, we report comprehensive inelastic neutron scattering (INS) measurements on single crystals of Sr$_{1-x}$Mn$_{1-y}$Sb$_2$, which have been well characterized by magnetization and magnetotransport measurements, both of which demonstrate that the material is a topologically nontrivial semimetal. The INS spectra clearly show a spin gap of ~6 meV. The dispersion in the magnetic Mn layer extends up to about 76 meV, while that between the layers has a narrow band width of 6 meV. We find that the linear spin-wave theory using a Heisenberg spin Hamiltonian can reproduce the experimental spectra with the following parameters: a nearest-neighbor ($S_{ij} \sim 28.0$ meV) and next-nearest-neighbor in-plane exchange interaction ($S_{ij} \sim 9.3$ meV), interlayer exchange coupling ($S_{ij} \sim -0.1$ meV), and spin anisotropy constant ($SD \sim -0.07$ meV). Despite the coexistence of Weyl fermions and magnons, we find no clear evidence that the magnetic dynamics are influenced by the Weyl fermions in Sr$_{1-x}$Mn$_{1-y}$Sb$_2$, possibly because that the Weyl fermions and magnons reside in the Sb and Mn layers separately, and the interlayer coupling is weak due to the quasi-two-dimensional nature of the material, as also evident from the small $S_{ij}$ of ~0.1 meV.

I. INTRODUCTION

Dirac semimetals are featured by two doubly-degenerate linear bands crossing at the Dirac point\cite{37}. The low-energy quasiparticle excitations near the Dirac point can be described by the $4 \times 4$ Dirac equation. In recent years, they have attracted a lot of attention because of their numerous exotic physical properties, such as high mobility\cite{16}, nontrivial $\pi$ Berry phase\cite{22}, and chiral-anomaly-induced negative magnetoresistance\cite{21,11}. Magnetic Dirac semimetals are particularly intriguing as they not only exhibit these fascinating phenomena but also offer a platform for investigating the interplay between Dirac fermions and spin dynamics. In this regard, the antiferromagnetic 12-type ternary compounds AMnPn$_2$ (A represents alkal- or rare-earth elements such as Sr, Ca, Ba, Yb, or Eu, and Pn = Sb, Bi) have been studied extensively\cite{12}. SrMnBi$_2$ was initially reported to be such a material\cite{13}. It was shown that the linearly dispersing $p$ bands of the Bi atoms formed highly anisotropic two-dimensional Dirac structure near the Fermi level, while the Mn bands were well below the Fermi level with binding energy larger than 2 eV and thus were localized\cite{14,18}. The localized divalent Mn ($3d^5$, spin $S = 5/2$) with a magnetic moment of magnitude $\sim 3.7\mu_B$ formed an antiferromagnetic structure below the Néel temperature $T_N$ of $\sim 300$ K\cite{25,21}. Similar results with Dirac fermions and magnons in the Bi- and Mn-square layers respectively were found by replacing Sr with Ca (Refs 10–13, 20, 23), Ba (Refs 24 and 25), and Yb (Refs 26–30). However, in the AMnBi$_2$ materials, the strong spin-orbital coupling (SOC) of Bi atoms might induce a gap that prevented the formation of the Dirac point, and made the fermions massive\cite{13,9,8,12}. One way to avoid the SOC-induced electronic gap opening and preserve the Dirac band structure is to replace Bi with lighter elements that have weaker SOC, e.g., Sb (Ref. 35). As a consequence, a number of AMnSb$_2$-type materials where A represents Ca (Ref. 36), Sr (Refs 37–40), Ba (Refs 35, 11, and 12), or Yb (Refs 43 and 44) have been discovered.

Among these materials, Sr$_{1-x}$Mn$_{1-y}$Sb$_2$ with Sr and Mn deficiencies stood out. It was suggested to be a magnetic Weyl semimetal which breaks the time-reversal symmetry\cite{17,23,36}, as opposed to non-magnetic ones that break the spatial inversion symmetry\cite{17,49}. Similar to AMnBi$_2$-type magnetic Dirac materials, Sr$_{1-x}$Mn$_{1-y}$Sb$_2$ was shown to exhibit fascinating properties that originated from the two-dimensional Sb and Mn square nets [Fig. 1(a)] (Ref. 37). Furthermore, the reduced size of the SOC because of the lighter mass of Sb as compared to Bi resulted in a nearly massless topological fermion behavior ($m^* = 0.04 - 0.05m_0$, where $m^*$ and $m_0$ are the effective and free-electron masses, respectively)\cite{25}. More importantly, it was shown that below the $T_N$ of 304 K,
the material underwent a transition to a canted antiferromagnetic phase with a ferromagnetic component of 0.2 $\mu_B$ (Ref. [57]). This small but finite ferromagnetic moment was proposed to break the time-reversal symmetry, lift the degeneracy of the electron bands, and lead to the long-sought magnetic Weyl semimetal state [20,17,15].

However, despite extensive studies on the aforementioned materials, whether and how the topological fermions interplay with the magnons are still unsettled issues. In CaMnBi$_2$, it was shown that there was a weak resistivity anomaly at the $T_N$, indicative of a coupling between the Dirac bands and the magnetic ground state [20,21], but no such anomaly was found in other reports [22,23]. A two-magnon Raman scattering study of CaMnBi$_2$ and SrMnBi$_2$ indicated that Dirac carriers significantly enhanced the exchange coupling between the magnetic layers ($J_e$), and a spin-fermion model showed that this in turn drove a charge-gap opening along the Dirac locus [24]. However, an inelastic neutron scattering (INS) study suggested that the $J_e$ estimated from the Raman measurements might have been exaggerated due to the neglecting of the single-ion spin anisotropy [25], and instead it was found that the Dirac fermions did not affect the spin dynamics at all [26]. In YbMnBi$_2$, nearly wave-vector independent damping in the INS spectra was taken as a signature of the spin-fermion coupling [27]. In contrast, another INS work did not detect any anomalous features in the magnetic spectra, implying the absence of the coupling between magnons and topological fermions [28].

In this work, we have carried out INS together with magnetization and magnetotransport measurements on single crystals of Sr$_{1-x}$Mn$_{1-y}$Sb$_2$. We observe strong de Haas van Alphen (dHvA) and Shubnikov de Hass (SdH) quantum oscillations at 2 K, from which we find topological fermions with $m^* = 0.10m_0$ and a nontrivial Berry phase, consistent with this material being a magnetic Weyl semimetal [29]. Our INS study reveals clear magnetic spectra dispersing from 6 meV and extending up to $\sim$76 meV. The spin-wave spectra can be well described by a localized Heisenberg model with a nearest-neighbor ($SJ_1 \sim 28.0$ meV) and next-nearest-neighbor in-plane exchange interaction ($SJ_2 \sim 9.3$ meV), and interlayer exchange coupling ($SJ_z \sim -0.1$ meV), along with a spin anisotropy term ($SD \sim -0.07$ meV). From our results, we do not observe signatures that the magnetic dynamics are affected by the topological fermions.

## II. EXPERIMENTAL DETAILS

Single crystals of Sr$_{1-x}$Mn$_{1-y}$Sb$_2$ were grown using Sb as the self flux, with an initial atomic ratio of Sr:Mn:Sb = 1:1:4 for the raw materials. An alumina crucible containing the raw materials was sealed under Ar atmosphere in a quartz tube. The sealed ampule was heated up to 850 °C, followed by a slow cooling at a rate of 1 °C/h and centrifuged at 660 °C. Single crystals with size up to $7 \times 5 \times 3$ mm$^3$ were so obtained, and some of the crystals are shown in Fig. 1(b). The composition of the single crystals was measured with energy dispersive spectroscopy (EDS) in an energy analyser (EX-250, Horiba) equipped in a scanning tunneling microscope (S-3400N II, Hitachi). Orientations of the crystals were determined by a single-crystal X-ray diffractometer (D8 Discover, Bruker) and a backscattering Laue X-ray diffractometer (LAUESYS, Photonic Science). Magnetization and resistivity measurements were conducted in a physical property measurement system (PPMS-9T, Quantum Design).

For INS experiments, single crystals were glued on aluminum plates by hydrogen-free Cytop grease. These crystals were well coaligned using a backscattering Laue X-ray diffractometer. Time-of-flight INS experiments were performed on 4SEASONS located at J-PARC Center in Japan [30], and MERLIN at ISIS Facility in the United Kingdom. We coaligned 27 pieces of single crystals weighed about 3.6 g in total for the experiment on 4SEASONS, and 16 pieces weighed about 4.2 g in total for the experiment on MERLIN. The single crystals on the plates were mounted in the $(H,0,L)$ plane, with the [010] direction aligned in the vertical direction. The assembly was loaded into a closed-cycle refrigerator. Both 4SEASONS and MERLIN were operated in a multiple-$E_i$ (incident energy) mode. For the experiment on 4SEASONS, we used a set of $E_i = 100.1$ (primary), 47.8, and 18.3 meV and a chopper frequency of 300 Hz. We set the angle of the neutron beam direction parallel to the c axis to be zero. Data were collected at 6 K by rotating the sample about the [010] direction with a range of 60° in a 0.3° step. On MERLIN, data were collected in the range of 90° in a 1° step at 6 K, with a set of $E_i = 90.2$ (primary), 31.8, and 16.0 meV and a chopper frequency of 300 Hz. We also conducted neutron scattering measurements at elevated temperatures on both spectrometers to investigate the temperature evolution of magnetic Bragg peaks. The wave vector $Q$ was described by $(HKL)$ reciprocal lattice unit (rilu) of $(a^*, b^*, c^*) = (2\pi/a, 2\pi/b, 2\pi/c)$. Although there is a small orthorhombicity suggested in Ref. [37], we used a tetragonal notation with $a \approx b = 4.4342$ Å, and $c = 23.1359$ Å. Note that we used the longest axis as c, which is the same as that in Refs [21] and [34] but different from that in Refs [37] and [40]. In this case, our (001) corresponds to their (100).

## III. RESULTS

### A. Sample Characterizations

We checked the orientation of the Sr$_{1-x}$Mn$_{1-y}$Sb$_2$ single crystals with single-crystal and backscattering Laue X-ray diffractometers, and the results are shown in Fig. 1(c) and (d), respectively. As shown in Fig. 1(a), the crystal has a layered structure with Sb and Mn atoms forming square nets [21,37]. The crystal naturally cleaves along the c axis, so the cleavage plane can be nicely in-
FIG. 1. (a) Crystal and magnetic structure of Sr$_{1-x}$Mn$_{1-y}$Sb$_2$ (space group No. 62, Pnma) with $a \approx b = 4.4342$, $c = 23.1359$ Å, and $\alpha = \beta = \gamma = 90^\circ$. Note that we only show half of the unit cell along the $c$ axis. Arrows represent the spins. The exchange paths are labeled with $J_1$ (nearest-neighbor), $J_2$ (next-nearest-neighbor), and $J_c$ (interlayer). (b) Coaligned single crystals we used for the inelastic neutron scattering measurements. (c) Single-crystal X-ray diffraction pattern of the cleavage plane. (d) Backscattering Laue x-ray diffraction pattern with the beam along the [001] direction. (e) Temperature dependence of the magnetization measured with magnetic field $B = 1$ T applied along the $c$ axis. (f) Temperature dependence of the integrated intensities of the magnetic Bragg peak (1, 0, 0). The solid line in (f) is a guideline to the eye. Arrows in (e) and (f) indicate the Néel temperature $T_N$.

dexed with $(0, 0, L)$ as shown in Fig. 1(c). The sharp $(0, 0, L)$ peaks in Fig. 1(c) and clear Laue pattern in Fig. 1(d) demonstrate the excellent crystallinity of the single crystals. EDS measurements on the single crystals show that there are approximately 1% Sr and 7% Mn deficiencies ($x < 0.1$, $y < 0.1$), which is commonly seen in this material. In fact, the magnetic properties of Sr$_{1-x}$Mn$_{1-y}$Sb$_2$ are influenced by the amount of deficiency. Samples with larger Sr and smaller Mn deficiencies display stronger ferromagnetic behavior, while those with larger Mn deficiency show weaker ferromagnetic behavior. According to the magnitude of the ferromagnetic saturated moment $M_s$, Ref. 37 categorized the samples into three types; $M_s \sim 0.1 - 0.6 \mu_B$/Mn for type A, $\sim 0.04 - 0.06 \mu_B$/Mn for type B, and $\sim 0.004 - 0.006 \mu_B$/Mn for type C. Our samples with larger Mn deficiency and weaker ferromagnetic behavior fall into the category of type C. The temperature dependence of the magnetization is shown in Fig. 1(e). At the $T_N$ of $\sim 304$ K, the magnetization starts to show a suppression due to the development of the antiferromagnetic order. This value is consistent with previous reports for this material. As shown in Fig. 1(a), the antiferromagnetic order has a canted ferromagnetic moment along the $a$ axis. At low temperatures, the ferromagnetic moment develops and gives rise to the magnetization upturn shown in Fig. 1(c). Such an upturn has also been observed in Ref. 37. The magnitude of the upturn corresponds to the strength of the ferromagnetic moment and depends on the stoichiometry, especially the amount of the Mn deficiency of the sample. Therefore, we suspect that the kink around 40 K in Fig. 1(e) is due to the presence of a small amount of second phase with a slightly different stoichiometry. In Fig. 1(f), we plot the temperature dependence of the integrated intensities of the magnetic Bragg peak (1, 0, 0), from which we observe that the peak intensity has an onset at the $T_N$ of 304 K upon cooling. These results are consistent with previous literatures on this material.
B. Topological Electronic Properties

![Graphs and equations related to the electronic properties of Sr$_{1-x}$Mn$_{1-y}$Sb$_2$](image)

We first probed the electronic properties of Sr$_{1-x}$Mn$_{1-y}$Sb$_2$ by measuring the resistivity and magnetization under external magnetic field. In Fig. 2(a), we plot the in-plane longitudinal ($\rho_{xx}$) and transverse (Hall) ($\rho_{xy}$) resistivity as a function of magnetic field applied along the $c$ axis at 2 K. In Fig. 2(b), we plot the in-plane conductivity $\sigma_{xx}$, which is converted from the $\rho_{xx}$ and $\rho_{xy}$, using $\sigma_{xx} = \rho_{xx} / (\rho_{xx}^2 + \rho_{xy}^2)$. By subtracting the background, we obtain the oscillatory component $\Delta \sigma_{xx}$, as shown in the inset of Fig. 2(b). These strong SdH oscillations at moderate magnetic field suggest the high mobility and light effective mass of the carriers. Furthermore, the large SdH oscillation amplitude is also an indication of the quasi-two-dimensional electronic structure of the material. In this study, we focus on the type-C samples. Compared to type-A and type-B samples which have larger saturated ferromagnetic moments, type-C samples exhibit relatively weak quantum oscillations due to the large $\rho_{xy}$. Moreover, SdH oscillations originate from the oscillating scattering rate and the details depend on the actual scattering mechanisms. This sometimes makes the Lifshitz-Kosevich (LK) theory not accurate in describing experimental observations, as is the case for Sr$_{1-x}$Mn$_{1-y}$Sb$_2$ (Ref. 37). On the other hand, the dHvA effect is caused directly by the oscillations of electrons’ free energy and can be well described by the LK model for both three- and two-dimensional systems. Among the three types of samples, type C exhibits the strongest dHvA oscillations due to the weak ferromagnetic background. As shown in Fig. 2(c), the magnetization shows very clear oscillations at moderate fields. Therefore, we use dHvA oscillations for detailed analyses of the electronic properties for our type-C samples below.

By subtracting the background of the magnetization, we obtain the oscillatory component of the magnetization $\Delta M$ as a function of magnetic field $B$ [Fig. 2(d)]. The oscillatory component can be described by the LK formula, as $\Delta M \propto -B^{-\lambda}R_T R_B R_S \sin[2\pi(F/B - \gamma + \delta)]$, where the exponent $\lambda$ is $1/2$ and 0 for the three- and two-dimensional cases, respectively; Onsager phase factor $\gamma = 1/2 - \phi/2\pi$, and $\delta$ is the shift, taking the value of $\pm1/8$ and 0 for three- and two-dimensional cases, respectively; $F$ and $\phi$ are the oscillation frequency and Berry phase, respectively; $R_T = (2 \pi k_B T / \hbar \omega_c) / \sinh(2 \pi k_B T / \hbar \omega_c)$, and $R_D = \exp(-2 \pi^2 k_B T \omega_c) / \omega_c$, with $\omega_c$ and $T_D$ being the cyclotron frequency and Dingle temperature, respectively. $R_S = \cos(\pi g m^* / m_0)$ is the spin damping factor due to the Zeeman splitting, which can be neglected in the present case, as we do not observe any sign of Landau level splitting in the oscillations at $T = 2$ K under $B = 9$ T. Here, $m^*$ and $m_0$ are the effective mass and rest mass of the free electrons, respectively.

Since the cyclotron frequency $\omega_c eB / m^*$, the only temperature-dependent term in $\Delta M$ can be written as,

$$R_T = (2 \pi^2 k_B T / \hbar \omega_c) / \sinh(2 \pi^2 k_B T / \hbar \omega_c) \approx (14.69 m^* T / B) / \sinh(14.69 m^* T / B).$$

We have fitted the temperature dependence of the amplitude of $\Delta M$ using this formula, and the results are shown in Fig. 2(c). We obtain an effective mass of 0.10(3)$m_0$ for the sample by averaging the results obtained at several fields. This value is similar to those of NbP (Ref. 55), ZrSiS (Ref. 56), and Cd$_3$As$_2$ (Ref. 57) and (Ref. 58). This effective mass is slightly different from that in Ref. 57, which may
be caused by the composition difference and the limited magnetic field range in our study.

To obtain the Berry phase $\phi$ of Sr$_{1-x}$Mn$_{1-y}$Sb$_2$, we can use the Onsager quantization rule to construct the Landau-level fan diagram. However, as observed in Fig. 2(d), there appear to be two oscillating frequencies. We perform fast Fourier transform analysis of the dHvA oscillation as shown in the inset of Fig. 2(f). This clearly shows two frequencies of $F_1 \approx 73.2$ T and $F_2 \approx 57.2$ T, similar to the values for the type-C samples in Ref. 37. These values are in excellent agreement with the angle-resolved photoemission spectroscopy data and band structure calculations for this material.38 39 40 We further analyze the dHvA data with a two-frequency LK model, and the results are shown in Fig. 2(f). From the LK fit, we obtain the Berry phase of $0.3\pi$ and $\pi$ corresponding to the bands of 73.2 and 57.2 T, respectively. These strongly indicate that the band structure is topologically nontrivial. We have measured the resistivity and magnetizations for other type-C samples. Although the details depend on the stoichiometry of the samples, different from Ref. 40, the high-energy behavior in Fig. 3(c) is different from that in Ref. 40, possibly because we use type-C samples, different from Ref. 40. In Fig. 3(d), we plot the dispersion along the [001] direction. The out-of-plane dispersion also exhibits a clear spin gap at 6 meV, and the total band width is about 5 meV, an order of magnitude smaller than those in the plane shown in Fig. 3(a) and (b), consistent with the quasi-two-dimensional crystal structure of this material. The magnetic excitations with a spin gap of 6 meV, highly dispersive in the plane, but weakly dispersive out of the plane, are qualitatively similar to those in related magnetic Dirac materials such as CaMnBi$_2$, SrMnBi$_2$, and YbMnBi$_2$. These spin-wave excitations remain well defined at high energies, distinct from some iron-based superconductors where the high-energy excitations are strongly damped and the spin waves decay into a Stoner continuum.41 42

To visualize the magnetic excitations in the momentum space, we plot a series of constant-energy contours in the $(HK0)$ plane with energies up to 70 meV in Fig. 4. At an energy transfer of $\Delta E = 10 \pm 2$ meV, slightly above the spin gap of 6 meV, there are both magnetic and lattice excitations. For instance, in Fig. 4(a), there is a strong peak at $(1, 0, 0)$, which corresponds to a magnetic Bragg peak at the elastic position. On the other hand, the peaks at $(-1, 0, 0)$ are phonons, which disappear at higher energies, as the phonon intensities decrease rapidly as the energy increases. The spin waves disperse outwards as the energy increases and form a ring centered at $(1, 0, 0)$ as shown in Fig. 4(b); upon further increasing the energy to 50 meV, the ring evolves into a square. At 70 meV, slightly below the band top, there are still well-resolved magnetic excitations. The clear patterns of the spin waves allow us to obtain an accurate parameterization of the spectra, as we discuss below.

To analyze the data, we use the following Hamiltonian:

$$\hat{H} = \sum_{\langle i,j \rangle} J_{ij} \hat{S}_i \cdot \hat{S}_j - \sum_i D(\hat{S}_i^z)^2,$$

where we include a nearest-neighbor ($J_1$) and next-nearest-neighbor ($J_2$), and interlayer exchange coupling constant ($J_z$). The exchange paths are illustrated in Fig. 1(a). To account for the spin gap, we include a single-ion anisotropy term $D$. Based on the linear spin-wave theory and SPINW package, we calculated the spin-spin correlation function:

$$S^{\alpha\beta}(Q, \omega) = \frac{1}{N} \sum_{i,j} e^{iQ(r_i-r_j)} \int_{-\infty}^{\infty} \langle \hat{S}_i^\alpha \hat{S}_j^\beta(t) \rangle e^{-i\omega t} dt,$$

which is related to scattering cross section

$$\frac{d^2\sigma}{d\Omega d\omega} \propto |F(Q)|^2 \sum_{i,j} (\delta_{\alpha\beta} - \frac{Q_i Q_j}{Q^2}) S^{\alpha\beta}(Q, \omega),$$
FIG. 3. Magnetic dispersions of Sr$_{1-x}$Mn$_{1-y}$Sb$_2$ measured at 6 K together with the theoretical calculation results. (a) and (b) Dispersions along the [100] and [110] directions, respectively, obtained on 4SEASONS with $E_i = 100.1$ meV. (c) and (d) Dispersions along the [100] and [001] directions obtained on MERLIN with $E_i = 16$ meV. Panel (c) focuses on the low-energy part of (a) to show the spin gap. In panels (a), (b), and (d), solid lines are the calculated dispersions. The calculated dispersions with intensities are shown on the right hand side of each panel to be compared with the experimental data on the left hand side. Data in (a) and (c) were integrated with $K = [-0.2, 0.2]$ rlu, and all available $L$s; data in (b) with a thickness of 0.1 rlu about each momentum along the [-110] direction; data in (d) with $H = [0.8, 1.2]$ rlu, and $K = [-0.2, 0.2]$ rlu. The dashed line in (c) illustrates an energy scan at (100). The scan profile is plotted on the right hand side with the energy and intensity being the $y$ and $x$ axis, respectively. The arrow indicates the gap value. In (d), the low-energy part below about 4.5 meV is due to the Bragg peaks and some spurious signals, and the broad experimental data can be reproduced by spin-wave calculations convoluting the instrumental resolution.$^{21}$

where $\alpha$ and $\beta$ are direction indices ($xyz$), $F(Q)$ is the magnetic structure factor, $S_i$ is the spin at site $i$ with the coordinate $r_i$, and $N$ is the total number of sites. In Figs 3 and 4, the calculated spectra using $SJ_1 \sim 28.0$, $SJ_2 \sim 9.3$, $SJ_c \sim -0.1$, and $SD \sim -0.07$ meV are plotted on the right hand side of the experimental results in Fig. 3(a), (b), and (d). Furthermore, the calculated dispersions are plotted as solid lines on top of the experimental dispersions. It is clear that the calculations are in excellent agreement with the experimental data, including the dispersions in and out of plane, the spin anisotropy gap, and the spectral weight distribution in
FIG. 4. Contour maps of the constant-energy cuts measured with $E_i = 100.1$ meV at 6 K. The experimental data are shown on the left hand side of each panel, while the theoretical results are shown on the right hand side. The energy range of the integration is shown on the top of each panel. All the data are from 4SEASONS.

the momentum space. The parameters we used in these calculations, and the gap as well as the $T_N$ are tabulated in Table I together with data for other related materials.

There are a few remarks we want to make about the calculations and fittings. First, since there are four Mn atoms in each unit cell\textsuperscript{37}, there are four spin-wave branches in the calculations as shown in Fig. 3(a) and (b). However, due to the resolution limit, we are not able to resolve these four branches experimentally. Second, the structure factor is small for $Q$ ranging from (-0.5, 0, 0) to (0.5, 0, 0), consistent with the experimental observations of vanishing scattering intensities in this range. Third, a positive $J_2$ is needed to account for the local minimum at (-0.5, 0.5, 0), as shown in Fig. 3(b). The perfect match of the calculated dispersion and the experimental spectra further demonstrates the quality of the fits. Without such a $J_2$, the local minimum is absent, as shown in Ref.\textsuperscript{40}. The same sign of $J_1$ and $J_2$ intro-
TABLE I. Exchange parameters, single-ion anisotropy constants, spin gaps, ordering temperature \( T_N \), and related references. Values in the brackets denote the errors.

|                  | \( SJ_1 \) (meV) | \( SJ_2 \) (meV) | \( SJ_C \) (meV) | \( SD \) (meV) | \( \Delta \) (meV) | \( T_N \) (K) | References   |
|------------------|----------------|----------------|----------------|---------------|----------------|----------------|--------------|
| \( \text{Sr}_{1-x}\text{Mn}_{1-y}\text{Sb}_2 \) | 28.0(2)       | 9.27(36)       | -0.10(1)       | -0.07(8)      | ~6.0          | ~304           | our work     |
| \( \text{Sr}_{1-x}\text{Mn}_{1-y}\text{Sb}_2 \) | 23.25(75)     | negligible     | -0.65(20)      | diag(0.30(13) 0.8(3) 0)* | ~8.5          | ~304           | [40]         |
| \( \text{SrMnBi}_2 \) | 21.3(2)       | 6.39(15)       | 0.11(2)        | 0.31(2)       | 10.2(2)       | 287(5)         | [21]         |
| \( \text{CaMnBi}_2 \) | 23.4(2)       | 7.9(5)         | -0.10(5)       | 0.18(3)       | 8.3(8)        | 264(2)         | [21]         |
| \( \text{YbMnBi}_2 \) | 25.2(2)       | 10.1(3)        | 0.131(4)       | -0.20(1)      | 9.0(2)        | ~290           | [31] and [51]|

*In Ref. [40], \( S^\alpha A^\alpha S^\beta \) was used to replace the \( SD \) in the Hamiltonian.

IV. DISCUSSIONS AND CONCLUSIONS

From the electrical transport and magnetization results, we find that \( \text{Sr}_{1-x}\text{Mn}_{1-y}\text{Sb}_2 \) hosts topological fermions, consistent with the proposal of magnetic Weyl semimetal state in this system [27]. On the other hand, we observe well-defined spin waves resulting from the Mn atoms, with no discernible damping due to the itinerant electrons. The spectra can be well fitted by a local moment Heisenberg model. From these data, we do not detect any effect of the itinerant electrons on the spin-wave excitations resulting from the Mn local moments. Similarly, in \( \text{CaMnBi}_2 \), \( \text{SrMnBi}_2 \), and \( \text{YbMnBi}_2 \), no influence of the Dirac fermions on the spin dynamics has been observed either. These behaviors are different from those in iron-based superconductors where itinerant electrons are believed to play an important role in damping the high-energy magnetic excitations and making the spin waves decay into a Stoner continuum [21,22].

In \( \text{Sr}_{1-x}\text{Mn}_{1-y}\text{Sb}_2 \), the magnetic excitations are resulting from the local moments in the Mn layers, whereas the itinerant electrons are contributed by the Sb layers which are separated from the former by \( c \)-axis constants of 23.1359 Å. The large SdH oscillation amplitude also indicates that the electronic structure for \( \text{Sr}_{1-x}\text{Mn}_{1-y}\text{Sb}_2 \) is two-dimensional like. Furthermore, the spin-wave spectra indicate that the magnons are quasi-two-dimensional as well. Our fitting indicates that \( SJ_1 \) and \( SJ_2 \) are 28.0 and 9.27 meV, respectively, while \( J_c \) is only -0.10 meV, two orders of magnitude smaller. Taking these into account, it is not surprising that we do not observe the effect of the itinerant electrons on the spin dynamics. We believe this also explains the similar behavior in other magnetic Dirac semimetal systems [21]. Nevertheless, our results do not completely rule out the possible subtle influence of the itinerant electrons on the magnons.

Baring these in mind, in order to observe strong spin-fermion coupling, it may be helpful to look for quasi-twodimensional magnetic Dirac or Weyl semimetals with stronger interlayer couplings, or even three-dimensional materials. A more ideal case will be that the magnons and fermions are in the same layer or arising from the same atoms like in iron-based superconductors [66,67]. The recently discovered magnetic Weyl semimetal \( \text{Co}_3\text{Sn}_2\text{S}_2 \) may be such an example. In this material, it was shown that the Weyl nodes were close to the Fermi level [68]. Furthermore, it exhibited both high anomalous Hall effect and large anomalous Hall angle, indicating strong coupling between the magnetism and electronic transport. It would be of great interest to further explore the possible spin-fermion coupling in this and other related materials [71].

Likewise, to investigate the spin-fermion interactions, one can also make discussions in the context of how the electronic structures are affected by the magnetism. For example, in a magnetic Weyl semimetal \( \text{Mn}_3\text{Sn} \), it was suggested that the helical magnetic ordering observed in the INS measurements could remove the Weyl nodes in the helical phase [22].

However, it is not clear how the inclusion of a substantial \( J_2 \) as shown in our current work and typically present in these materials (Table I), will affect the results. It will
be beneficial to carry out angle-resolved photoemission spectroscopy measurements to test these proposals.

To conclude, while our electrical transport and magnetization measurements indicate that Sr$_{1-x}$Mn$_{1-y}$Sb$_2$ is a topological semimetal, our INS data reveal well-defined spin waves resulting from the Mn local moments, which can be nicely described using a Hamiltonian including $S J_1 \sim 28.0$ meV, $S J_2 \sim 9.3$ meV, $S J_3 \sim -0.1$ meV, and $S D \sim -0.07$ meV. Our results suggest that the topological fermions do not impact the magnons. We propose this to be due to the separated layers of the localized spins and itinerant carriers and the weak interlayer coupling.

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1. N. P. Armitage, E. J. Mele, and Ashvin Vishwanath, “Weyl and Dirac semimetals in three-dimensional solids,” Rev. Mod. Phys. 90, 015001 (2018).
2. T. O. Wehling, Annica M Black-Schaffer, and Alexander V Balatsky, “Dirac materials,” Adv. Phys. 63, 1–76 (2014).
3. Oskar Vafek and Ashvin Vishwanath, “Dirac fermions in solids: From high-Tc cuprates and graphene to topological insulators and Weyl semimetals,” Annu. Rev. Condens. Matter Phys. 5, 83–112 (2014).
4. A. H. Castro Neto, F. Guinea, N. M. R. Peres, K. S. Novoselov, and A. K. Geim, “The electronic properties of graphene,” Rev. Mod. Phys. 81, 109–162 (2009).
5. Tian Liang, Quinn Gibson, Mazhar N. Ali, Minbao Liu, R. J. Cava, and N. P. Ong, “Ultrahigh mobility and giant magnetoresistance in the Dirac semimetal Cd$_2$As$_2$,” Nat. Mater. 14, 280–284 (2015).
6. Chandra Shekhar, Ajaya K. Nayak, Yan Sun, Marcus Schmidt, Michael Nicklas, Inge Leermakers, Uli Zeitler, Yurii Skourski, Jochen Wosnitza, Zhongkai Liu, Yulin Chen, Walter Schnelle, Horst Borrmann, Yuri Grin, Claudia Felser, and Binghai Yan, “Extremely large magnetoresistance and ultra-high mobility in the topological Weyl semimetal candidate NbP,” Nat. Phys. 11, 645–649 (2015).
7. Yuanbo Zhang, Yan-Wen Tan, Horst L. Stormer, and Philip Kim, “Experimental observation of the quantum Hall effect and Berry’s phase in graphene,” Nature 438, 201–204 (2005).
8. L. P. He, X. C. Hong, J. K. Dong, J. Pan, Z. Zhang, J. Zhang, and S. Y. Li, “Quantum transport evidence for the three-dimensional Dirac semimetal phase in Cd$_2$As$_2$,” Phys. Rev. Lett. 113, 246402 (2014).
9. Shichao Li, Zhaopeng Guo, Dongzhi Fu, Xing-Chen Pan, Jinghui Wang, Kejing Ran, Song Bao, Zhen Ma, Zhengwei Cai, Rui Wang, Rui Yu, Jian Sun, Fengqi Song, and Jinsong Wen, “Evidence for a Dirac nodal-line semimetal in SrAs$_3$,” Sci. Bull. 63, 535–541 (2018).
10. Jun Xiong, Satya K. Kushwaha, Tian Liang, Jason W. Krizan, Max Hirschberger, Wudi Wang, R. J. Cava, and N. P. Ong, “Evidence for the chiral anomaly in the Dirac semimetal Na$_3$Bi,” Science 350, 413–416 (2015).
11. Qiang Li, Dmitri E. Kharzeev, Cheng Zhang, Yuan Huang, I. Pletikosić, A. Ting V. Fedorov, R. Ting D. Zhong, J. Ting A. Schneeloch, G. Ting D. Gu, and T. Valla, “Chiral magnetic effect in ZrTe$_5$,” Nat. Phys. 12, 550–554 (2016).
12. Sebastian Klemen, Shiming Lei, and Leslie M. Schoop, “Topological semimetals in square-net materials,” Annu. Rev. Mater. Res. 49, 185–206 (2019).
13. Joombum Park, G. Lee, F. Wolff-Fabris, Y. Y. Koh, M. J. Eom, Y. K. Kim, M. A. Farhan, Y. J. Jo, C. Kim, J. H. Shim, and J. S. Kim, “Anisotropic Dirac fermions in a Bi square net of SrMnBi$_2$,” Phys. Rev. Lett. 107, 126402 (2011).
14. Jiakui K. Wang, Liang L. Zhao, Quan Yin, G. Kotliar, M. S. Kim, M. C. Aronson, and E. Morosan, “Layered transition-metal pnictide SrMnBi$_2$ with metallic blocking layer,” Phys. Rev. B 84, 064428 (2011).
15. Kefeng Wang, D. Graf, Hechang Lei, S. W. Tozer, and C. Petrovic, “Quantum transport of two-dimensional Dirac fermions in SrMnBi$_2$,” Phys. Rev. B 84, 220401 (2011).
16. Geunsik Lee, Muhammad A. Farhan, Jun Sung Kim, and Ji Hoon Shim, “Anisotropic Dirac electronic structures of AMnBi$_2$ (A = Sr,Ca),” Phys. Rev. B 87, 245104 (2013).
17. Ya Feng, Zhijun Wang, Chaoyu Chen, Youguo Shi, Zhuojin Xie, Hemian Yi, Aiji Liang, Shaohong Le, Junfeng He, Yingying Peng, Xu Liu, Yan Liu, Lin Zhao, Guodong Liu, Xiaoli Dong, Jun Zhang, Chuangtian Chen, Zuyan Xu, Xi Dai, Zhong Fang, and X. J. Zhou, “Strong anisotropy of Dirac cones in SrMnBi$_2$ and CaMnBi$_2$ revealed by angle-resolved photoemission spectroscopy,” Sci. Rep. 4, 5385.
21 M. C. Rahn, A. J. Princep, A. Piovano, J. Kulda, Y. F. Guo, Y. G. Shi, and A. T. Boothroyd, “Spin dynamics in the antiferromagnetic phases of the Dirac metals AMnBi$_2$,” Phys. Rev. B 90, 035133 (2014).

22 L.-L. Jia, Z.-H. Liu, Y.-P. Cai, T. Qian, X.-P. Wang, Lijun Li, Kefeng Wang, D. Graf, Limin Wang, Aifeng Wang, I. Zaliznyak, Weijun Ren, Lijun Wu, D. Graf, Yi-Yan Wang, Qiao-He Yu, and Tian-Long Xia, “Dipanjan Chaudhuri, Bing Cheng, Alexander Yaresko, Andrew F. May, Michael A. McGuire, and Brian C. Sales, “Effect of Eu magnetism on the electronic properties of the candidate Dirac material EuMnBi$_2$,” Phys. Rev. B 90, 075109 (2014).

23 J.-B. He, D. M. Wang, and G. F. Chen, “Magnetotransport behavior caused by the zeroth Landau level in the candidate Dirac material EuMnBi$_2$,” Chin. Phys. B 25, 107503 (2016).

24 J. Y. Liu, J. Hu, D. Graf, T. Zou, M. Zhu, Y. Shi, S. Che, S. M. A. Radmanesh, C. N. Lau, L. Spini, H. B. Cao, X. Ke, and Z. Q. Mao, “Unusual interlayer quantum transport behavior caused by the zeroth Landau level in YbMnBi$_2$, Nat. Commun. 8, 3421 (2016).

25 J.-B. He, D. M. Wang, and G. F. Chen, “Large linear magnetoresistance in a new Dirac material BaMnBi$_2$, Chin. Phys. B 25, 107503 (2016).

26 M. Piovano, J. Kulda, Y. F. Guo, Y. G. Shi, and A. T. Boothroyd, “Spin dynamics in the antiferromagnetic phases of the Dirac metals AMnBi$_2$ (A = Sr, Ca),” Phys. Rev. B 95, 134405 (2017).

27 J. B. He, D. M. Wang, and G. F. Chen, “Large linear magnetoresistance in layered manganese pnictide CaMnBi$_2$, J. Phys. Condens. Matter 29, 010 (2017).

28 J. Y. Liu, J. Hu, Q. Zhang, D. Graf, H. B. Cao, S. M. A. Radmanesh, D. J. Adams, Y. L. Zhu, G. Ting F. Cheng, X. Liu, W. A. Phelan, J. Wei, M. Jaime, F. Balakirev, D. A. Tennant, J. F. DiTusa, I. Chiorescu, L. Spini, and Z. Q. Mao, “A magnetic topological semimetal Sr$_{1−y}$Mn$_{1−x}$Sb$_2$ (y, z < 0.1),” Nat. Mater. 16, 905–910 (2017).

29 S. V. Ramanikutta, J. Henke, A. Schiphorst, R. Nutakki, S. Bron, G. Araizi-Kanoutas, S. K. Mishra, Lei Li, Y. K. Huang, T. K. Kim, M. Hoesch, C. Schlueter, T. L. Lee, A. de Visser, Zhicheng Zhong, Jasper van Wezel, E. van Heumen, and M. S. Golden, “Electronic structure of the candidate 2D Dirac semimetal SrMnSb$_2$: A combined experimental and theoretical study,” SciPost Phys. 4, 010 (2018).

30 J. Liu, Tao Ma, Lin Zhou, Warren E. Strasheim, Farhan Islam, Brandt A. Jensen, Wei Tian, Thomas Heitmann, R. A. Rosenberg, J. M. Wilde, Bing Li, Andreas Kreyssig, Alan I. Goldman, B. G. Ueland, Robert J. Queeney, and David Vaknin, “Crystal growth, microstructure, and physical properties of SrMnSb$_2$, Phys. Rev. B 99, 054435 (2019).

31 Qi Zhang, Satoshi Okamoto, Matthew B. Stone, Jinyu Liu, Yanglin Zhu, John DiTusa, Zhiqiang Mao, and David Alan Tennant, “Influence of magnetism on Dirac semimetallic behavior in nonstoichiometric Sr$_{1−y}$Mn$_{1−x}$Sb$_2$ (y ~0.07; z ~0.02),” Phys. Rev. B 100, 205105 (2019).

32 Jinyu Liu, Jin Hu, Huibo Cao, Yanglin Zhu, Alyssa Chuang, D. Graf, D. J. Adams, S. M. A. Radmanesh, L. Spini, I. Chiorescu, and Zhiqiang Mao, “Nearly massless Dirac fermions hosted by Sb square net in BaMnSb$_2$, Sci. Rep. 6, 30525 (2016).

33 Ji Liu, Lin Hu, and S. W. Arshad Farhan, Gemsnik Lee, and Ji Hoon Shim, “AcMnSb$_2$ (Ae=Sr, Ba): A new class of Dirac materials,” J. Phys.: Condens. Matter 26, 042201 (2014).

34 J. B. He, Y. Fu, L. X. Zhao, H. Liang, D. Y. Chen, Y. M. Leng, M. X. Wang, J. Li, S. Zhang, M. Q. Xue, C. H. Li, P. Zhang, Z. A. Ren, and G. F. Chen, “Quasi-two-dimensional massless Dirac fermions in CaMnBi$_2$, Phys. Rev. B 95, 045127 (2017).

35 J. Y. Liu, J. Hu, Q. Zhang, D. Graf, H. B. Cao, S. M. A. Radmanesh, D. J. Adams, Y. L. Zhu, G. Ting F. Cheng, X. Liu, W. A. Phelan, J. Wei, M. Jaime, F. Balakirev, D. A. Tennant, J. F. DiTusa, I. Chiorescu, L. Spini, and Z. Q. Mao, “A magnetic topological semimetal Sr$_{1−y}$Mn$_{1−x}$Sb$_2$ (y, z < 0.1),” Nat. Mater. 16, 905–910 (2017).

36 S. V. Ramankutty, J. Henke, A. Schiphorst, R. Nutakki, S. Bron, G. Araizi-Kanoutas, S. K. Mishra, Lei Li, Y. K. Huang, T. K. Kim, M. Hoesch, C. Schlueter, T. L. Lee, A. de Visser, Zhicheng Zhong, Jasper van Wezel, E. van Heumen, and M. S. Golden, “Electronic structure of the candidate 2D Dirac semimetal SrMnSb$_2$: A combined experimental and theoretical study,” SciPost Phys. 4, 010 (2018).

37 Yong Liu, Tao Ma, Lin Zhou, Warren E. Strasheim, Farhan Islam, Brandt A. Jensen, Wei Tian, Thomas Heitmann, R. A. Rosenberg, J. M. Wilde, Bing Li, Andreas Kreyssig, Alan I. Goldman, B. G. Ueland, Robert J. Queeney, and David Vaknin, “Crystal growth, microstructure, and physical properties of SrMnSb$_2$, Phys. Rev. B 99, 054435 (2019).

38 Qi Zhang, Satoshi Okamoto, Matthew B. Stone, Jinyu Liu, Yanglin Zhu, John DiTusa, Zhiqiang Mao, and David Alan Tennant, “Influence of magnetism on Dirac semimetallic behavior in nonstoichiometric Sr$_{1−y}$Mn$_{1−x}$Sb$_2$ (y ~0.07; z ~0.02),” Phys. Rev. B 100, 205105 (2019).

39 Jinyu Liu, Jin Hu, Huibo Cao, Yanglin Zhu, Alyssa Chuang, D. Graf, D. J. Adams, S. M. A. Radmanesh, L. Spini, I. Chiorescu, and Zhiqiang Mao, “Nearly massless Dirac fermions hosted by Sb square net in BaMnSb$_2$, Sci. Rep. 6, 30525 (2016).

40 Silu Huang, Jisun Kim, W. A. Shelton, E. W. Plummer, and Rongying Jin, “Nontrivial Berry phase in magnetic BaMnSb$_2$ semimetal,” Proc. Natl Acad. Sci. USA 114, 6256–6261 (2017).
hong Wang, Walter Schnelle, Steffen Wirth, Yulin Chen, Sebastian T. B. Goennenwein, and Claudia Felser, “Giant anomalous Hall effect in a ferromagnetic kagomé-lattice semimetal,” Nat. Phys. 14, 1125–1131 (2018).

Qi Wang, Yuanfeng Xu, Rui Lou, Zhonghao Liu, Man Li, Yaobo Huang, Dawei Shen, Hongming Weng, Shancai Wang, and Hechang Lei, “Large intrinsic anomalous Hall effect in half-metallic ferromagnet Co$_3$Sn$_2$S$_2$ with magnetic Weyl fermions,” Nat. Commun. 9, 3681 (2018).

Ilya Belopolski, Kaustuv Manna, Daniel S. Sanchez, Guoqing Chang, Benedikt Ernst, Jiaxin Yin, Songtian S. Zhang, Tyler Cochran, Nana Shumiya, Hao Zheng, Badur Singh, Guang Bian, Daniel Multer, Maksim Litskevich, Xiaoting Zhou, Shin-Ming Huang, Baokai Wang, Tay-Rong Chang, Su-Yang Xu, Arun Bansil, Claudia Felser, Hsin Lin, and M. Zahid Hasan, “Discovery of topological Weyl fermion lines and drumhead surface states in a room temperature magnet,” Science 365, 1278–1281 (2019).

Pyeongjae Park, Joosung Oh, Klara Uhlírová, Jerome Jackson, Andrés Dek, L szl Szunyogh, Ki Hoon Lee, Hwanbeom Cho, Ha-Leem Kim, Helen C. Walker, Devashibhai Adroja, Vladimir Sechovsky, and Je-Geun Park, “Magnetic excitations in non-collinear antiferromagnetic Weyl semimetal Mn$_3$Sn,” npj Quant. Mater. 3, 63 (2018).