Kagome magnets usually hosts nontrivial electronic or magnetic states drawing great interests in condensed matter physics. In this paper, we report a systematic study on transport properties of kagome magnet TmMn$_6$Sn$_6$. The prominent topological Hall effect (THE) has been observed in a wide temperature region spanning over various magnetic phases and exhibits strong temperature and field dependence. This novel phenomenon due to non-zero spin chirality indicates possible appearance of nontrivial magnetic states accompanying with strong fluctuations. The planar applied field drives planar Hall effect(PHE) and anistropic magnetoresistivity(PAMR) exhibiting sharp disconnections in angular dependent planar resistivity violating the empirical law. By using an effective field, we identify a magnetic transition separating the PAMR into two groups belonging to various magnetic states. We extended the empirical formula to scale the field and temperature dependent planar magneto-resistivity and provide the understandings for planar transport behaviors with the crossover between various magnetic states. Our results shed lights on the novel transport effects in presence of multiple nontrivial magnetic states for the kagome lattice with complicated magnetic structures.

**INTRODUCTION**

Kagome magnets have emerged as an important platform to study electronic correlations and nontrivial topology[1,4]. The unique crystal structure, made of corner-sharing triangles, naturally has relativistic band crossings at the Brillouin zone corners hosting nontrivial topological electronic Dirac Fermion and a dispersionless flat band[7]. With inclusion of spin orbital coupling and magnetism, the system can host various nontrivial topological electronic or magnetic states such as magnetic Weyl Fermions, quantized anomalous Hall states, and non-zero spin texture etc[11,8]. Fabricating various magnetic structures in kagome compounds would effectively engineer exotic states with novel phenomena to study the interplay between electron and magnetism in condensed matter physics.

Recently, a rare-earth family of kagome magnets ReMn$_6$Sn$_6$ (Re is the rare earth elements) with a layered hexagonal structure has drawn great interest due to the rich magnetic states and various nontrivial topological band structures[3,10]. These materials usually consist of two sub magnetic lattices from different layers: (1) the magnetic kagome lattice made by Mn ions. (2) another magnetic lattice made by rare earth ions. The intra- or inter-layer magnetic interactions drive various magnetic structures and complicated magnetic phase diagrams. TmMn$_6$Sn$_6$ is typical one of these materials[14,19]. It forms a hexagonal $P6/mmm$ structure ($a = 5.514\, \text{Å}$, and $c = 8.994\, \text{Å}$) consisting of kagome planes Mn$_3$Sn separated by two inequivalent Sn$_3$ and Sn$_2$Tm layers as shown in Fig. 1(a). The temperature dependent resistivity reveals TmMn$_6$Sn$_6$ is a good metal with small anisotropy. Observed sharp kinks around 325 K in temperature dependent magnetization ($M(T)$) curves reveal a magnetic transition shown in Fig. 1(d). Below this transition, the collinear-antiferromagnetic structure transits to a heli-magnetic structure which is revealed by neutron scattering measurements and predicted to host chiral spin texture such as skyrmions[20–22]. Compared the light rare earth elements such as Y, Tm is a heavy rare earth element with $4f$ electron and strong spin-orbital coupling which may lead to stronger magnetic interactions hosting more complicated magnetic states.

In this paper, we systematically studied the magnetotransport properties of TmMn$_6$Sn$_6$. The prominent topological Hall effect are observed with an applied field in the $ab$ plane suggesting the emergence of exotic magnetic states with strong fluctuations. In presence of magnetic transitions, the planer Hall effect (PHE) and anisotropic magnetoresistivity (PAMR) do not obey the empirical law. Special for PAMR, the abrupt disconnections due to magnetic moment flops separate planar longitudinal resistivity $\rho_{xx}^P$ into different groups belonging to various magnetic states. To describe these novel transport behavior, we scaled $\rho_{xx}^P$ by defined an effective field $\mu_0 H^*$ to acquire the critical field. By modifying the empirical law we scaled angular dependent $\rho_{xx}$ at various fields and provide the understanding for these planar transport behaviors spanning over various magnetic states.

**EXPERIMENTAL DETAIL**

Single crystals of TmMn$_6$Sn$_6$ were grown via the self-flux method. Tm, Mn, and Sn metals were mixed and sealed inside an evacuated quartz tube. After that, the mixture was first heated to 1100°C and then slowly cooled to 550°C where flux was removed by using a centrifuge. Large plates of single crystals are obtained with a typical size of $5 \times 5 \times 1\, \text{mm}^3$. The crystal structure and elemental composition
were confirmed by X-ray diffraction (XRD) measurements and Energy-dispersive X-ray spectroscopy (EDS). The [001] peaks were observed in XRD patterns indicating the high quality of our crystals shown in Fig. 1(a). The selected single crystals were shaped into a rectangular slice for electric and magnetic transport measurements. The six gold contacts were made on the ac plane with the current along the c axis of crystals as shown in Fig. 1(b). Electrical transport measurements were performed in the physical properties measurement system (PPMS Dynacool, Quantum Design). Magnetization measurements were performed in the vibrating sample magnetometer (VSM) module of the PPMS.

RESULTS AND DISCUSSION

Topological Hall Effect

The field dependent magnetization $M(\mu_0H)$, longitudinal and Hall resistivity $\rho_{xx}(\mu_0H)$ and $\rho_{xy}(\mu_0H)$ are shown in Fig. 2 with the applied field perpendicular to the ac plane ($\mu_0H \perp ab$). $M(\mu_0H)$ curves exhibit several obvious kinks and non-monotonic field dependence suggesting the emergence of multiple magnetic phase transitions in consistent with former reports [16]. Based on different slopes of $M(\mu_0H)$, two critical fields $\mu_0 H_{c1}$ and $\mu_0 H_s$ are identified dividing the magnetic phase diagram roughly into three regions (I, II, and III). In fact around $\mu_0 H_{c1}$ multiple transitions are observed. But since these transitions are very close, we denote the metamagnetic transition field by a single variable $\mu_0 H_{c1}$ in this paper. With decreasing the temperature $T$ from 300 K to 150 K, $\mu_0 H_{c1}$ and $\mu_0 H_s$ shifts to higher fields. Below 100 K with further decreasing $T$, $\mu_0 H_{c1}$ and $\mu_0 H_s$ shift to lower fields gradually. In region I ($\mu_0 H \leq \mu_0 H_{c1}$), $\rho_{xx}(\mu_0H)$ exhibits positive field response. With increasing $\mu_0 H$, $\rho_{xx}(\mu_0H)$ exhibits negative magnetoresistivity in regions II and III with a slope changing around $\mu_0 H_s$ as shown in Fig. 2(a). Correspondingly, $\rho_{xy}(\mu_0H)$ exhibits different field dependence in various regions with the slope changing at corresponding critical fields. Especially it is noticed that in region II, a prominent peak is observed at a characteristic field $\mu_0 H_T$. This anomaly becomes unapparent with decreasing $T$ and disappears around 100 K.

In a magnetic system, the Hall effect generally originates from
two contributions: (1) normal Hall effect (NHE) due to the Lorentz force and (2) anomalous Hall effect (AHE) due to magnetization or Berry curvature. For \( \text{TmMn}_6\text{Sn}_6 \), the discrepancy between \( \rho_{xy} \) and \( M \) around \( H_T \) suggests an additional contribution from topological Hall effect (THE) besides NHE and AHE. Thus, the total Hall resistivity can be expressed as:

\[
\rho_{xy} = \rho_{xy}^N + \rho_{xy}^A + \rho_{xy}^T = R_0 \mu_0 H + S_H \rho_{xx}^2 M + \rho_{xy}^T
\]

where \( R_0 \) is the Hall coefficient, \( S_H \) is a constant for the intrinsic anomalous Hall conductivity \( (\sigma_{xy}^A \sim \rho_{xy}^A / \rho_{xx}^2) \), which is linearly proportional to \( M \), and \( \rho_{xy}^N \), \( \rho_{xy}^A \), and \( \rho_{xy}^T \) are the normal Hall resistivity, anomalous Hall resistivity, and topological Hall resistivity respectively [23, 24]. According to this formula, the curves of \( \rho_{xy}(\mu_0 H) / \mu_0 H \) vs \( \rho_{xx}(\mu_0 H)^2 M(\mu_0 H) / \mu_0 H \) at various temperatures are scaled to separate various Hall contributions for \( \text{TmMn}_6\text{Sn}_6 \) shown in Fig. 3(a)[11]. By fitting the linear parts where the \( \rho_{xy}^T \) term disappears \( R_0(T) \) and \( S_H(T) \) are acquired shown in Fig. 3(b).

The \( \rho_{xy}^N \) and \( \rho_{xy}^A \) terms are calculated and subtracted from the total Hall resistivity to obtain \( \rho_{xy}^T \).

The temperature dependence of \( \rho_{xy}^T \) are presented in Fig. 3(d). The prominent THE signal is observed in high-temperature region and shrinks with decreasing the \( T \). Below 100 K, the \( \rho_{xy}^T \) becomes invisible. Usually THE is considered to origin from the movement of skyrmions in non-centrosymmetric non-collinear magnets hosting the nonzero scalar spin chirality. Recently fluctuation-driven mechanism is proposed to describe THE in centrosymmetric system relating to a special nontrivial magnetic phase [9][11]. To further understand the THE in \( \text{TmMn}_6\text{Sn}_6 \), we first analyze its magnetic phase diagram. In our measurements, three regions are identified shown in Fig. 3(c). According to former reports, with \( \mu_0 H < \mu_0 H_{c1} \) the revealed distorted spiral (DS) orders dominate the magnetic structure in region I above 50 K[9]. With \( \mu_0 H > \mu_0 H_s \), the saturate magnetization in \( M(\mu_0 H) \) curves suggests a force ferromagnetism (FF) state in region III. In region II, multiple possible magnetic transitions are suggested in region II by the observed disconnections in differential field dependent magnetization \( dM/d(\mu_0 H) \) and peaks in \( \rho_{xy}^T \) for \( \text{TmMn}_6\text{Sn}_6 \). In its analogue \( \text{YMn}_6\text{Sn}_6 \), transverse conical spiral (TCS) and fan-like (FL) states are observed in this region and TCS state is considered directly to relate to THE [9]. In \( \text{TmMn}_6\text{Sn}_6 \), the suggested magnetic states are more complicated than those in \( \text{YMn}_6\text{Sn}_6 \). In addition, the observed THE for \( \text{TmMn}_6\text{Sn}_6 \) probably spans over several magnetic region exhibiting strong \( \mu_0 H \) response in contrast to that only observed in the TCS state for \( \text{YMn}_6\text{Sn}_6 \). Thus, besides by large thermal fluctuations (such as observed in \( \text{YMn}_6\text{Sn}_6 \)) [25], non-zero chirality leading to large THE may be also driven by appearance of possible complicated magnetic phases such as nontrivial topological magnetic states. Further studies for magnetic phase diagram by neutron scattering are necessary and expected to reveal the microscopic nature for THE in \( \text{TmMn}_6\text{Sn}_6 \).

**Planar Hall effect and Anisotropic Magnetoresistivity**

To investigate the planar properties of \( \text{TmMn}_6\text{Sn}_6 \), the applied field \( \mu_0 H \) is rotated within \( ac \) plane of the crystal as shown in Fig. 4(a). \( \theta \) is defined as the angle between the current along the \( c \) axis of the crystal (When \( \mu_0 H / a, \theta=90^\circ \)). PHE, usually accompanied with PAMR, is a unique transport phenomenon driven by an in-plane magnetic-field-induced rotation of the principal axes of the resistivity tensor [26, 27] which can detect interplay of chirality, orbit, and spin for a quantum materials. Usually, the PHE and PAMR can be de-
FIG. 4. (a) The configuration for planar transport measurements of single crystal of TmMn$_6$Sn$_6$. The gray circular arrow indicates the rotating direction of the applied field. The current is along $c$ axis, and $\theta$ represents the angle between the applied field and current. (b) and (c) Angular dependent planar Hall resistivity $\rho_{xy}^P(\theta)$ and planar longitudinal resistivity $\rho_{xx}^P(\theta)$ at 10 K with $\mu_0H = 1$ T respectively. The black dash lines are the fitting curves by formulas (2). (d) and (e) $\rho_{xy}^P(\theta)$ and $\rho_{xx}^P(\theta)$ at 10 K with $\mu_0H = 1$ T, 2.5 T, 3 T, 4 T, 6 T, 10 T, 14 T respectively. $\rho_{xy}^P(\theta)$ is separated into ‘high’ and ‘low’ parts fitted by formula (4), marked by black dash lines.

scribed by empirical expressions as:

$$\rho_{xy}^P = \Delta \rho \sin \theta \cos \theta,$$

$$\rho_{xx}^P = \rho_{xx}^P - \Delta \rho \cos^2 \theta,$$

where $\rho_{xy}^P$ represents the in-plane Hall resistivity that directly shows the PHE, $\rho_{xx}^P$ is the PAMR, and $\Delta \rho = \rho_{xx}^P - \rho_{yy}^P$ is the resistivity anisotropy (called chiral resistivity in topological materials) with $\rho_{xx}^P$ and $\rho_{yy}^P$ representing the resistivity with the $\mu_0H$ perpendicular (90°) and parallel (0°) to the current respectively [26]. At 10 K with $\mu_0H = 1$ T, PHE and PAMR follow these empirical laws shown in Fig. 4(b) and (c). The angular dependent $\rho_{xy}^P(\theta)$ and $\rho_{xx}^P(\theta)$ exhibit two-fold oscillations with a 45°-angle shift during a whole rotating period (from 0° to 360°). With increasing $\mu_0H$, the amplitudes of oscillatory $\rho_{xy}^P(\theta)$ increase monotonously shown in Fig. 4(d) and angular dependence of $\rho_{xy}^P$ deviates from the empirical relation. Correspondingly, sudden jumps are observed in $\rho_{xx}^P(\theta)$ curves separating the data into two groups (‘High’ and ‘Low’ parts). These jumps exhibit strong field and angular dependence. The novel behaviors for PHE and PAMR are barely observed and studied before which are considered to relate to magnetic transitions for TmMn$_6$Sn$_6$.

To further investigate these novel PHE and PAMR, we define an effective field $\mu_0H^e = \mu_0H \sin \theta$ along the $a$ axis which drives the carriers to move along its perpendicular direction by a Lorentz force within semi-classic model. The $\rho_{xy}^P(\theta)$ and $\rho_{xx}^P(\theta)$ vs $\mu_0H \sin \theta$ are presented in Fig. 5. The weak kinks are observed in the butterfly-shape $\rho_{xy}^P(\theta)$ curves at an effective critical field of $\mu_0H^e = 2.4$ T. More clear features are observed in $\rho_{xx}^P(\theta)$ curves in Fig. 5(b). The sharp drops at various angle from Fig. 4(e) are scaled together at the same critical effective field separating $\rho_{xx}^P$ curves into two regions: (1) the high-resistivity part with $|\mu_0H^e| > \mu_0H^c$ and (2) the low-resistivity part with $|\mu_0H^e| \leq \mu_0H^c$. These behaviors are consistent with results acquired from the field dependent resistivity $\rho_{xy}^P(\mu_0H)$ and magnetization $M(\mu_0H)$ with $\mu_0H/\mu$ exhibiting jumps or kinks around the magnetic flop transition from DS to FF states [28]. The observed sud-
The amplitudes of oscillatory for each group can be extracted from $H_{c0}$ to normalize $\rho^{P}_{xx}$ and $\Delta P_{1,2}$, whereas the oscillatory amplitudes for different magnetic states. The data are fitted by this formula shown in Fig. 4(e).

Fig. 7 shows the temperature dependence of $\rho^{P}_{xy}(\theta)$ and $\Delta P_{1,2}^{P}(\theta)$ with $\mu_0 H = 14$ T. The derivation of empirical laws are observed in both $\rho^{P}_{xy}(\theta)$ and $\rho^{P}_{xx}(\theta)$ curves indicating the appearance of complicated magnetic states by changing $T$ in Figs. 7(a) and (b). By using the same scaling way, we analyze the planar transport properties evolving with changing $T$ shown in Figs. 7(c) and (d). The $\mu_0 H^c$ relating to the magnetic flop shifts to lower field region and becomes invisible gradually with increasing $T$. By using the extended formula, most of the curves are fitted with little derivations. In fact, with changing $T$ the system undergoes multiple magnetic transitions even with the same $\mu_0 H$ resulting in various MR responses. It is observed with $\mu_0 H^c > \mu_0 H^e$ the MR exhibits positive response and evolves to negative response gradually with changing $T$. Thus at some temperatures, rotating $\mu_0 H$ will drive more than two magnetic states with much broad transitions which leads to fail to fit $P^{P}_{xx}(\theta)$ by a general rule. For TmMnAsSn6, Tm and Mn construct the system’s magnetic structure together. The Tm$^{3+}$ ions with $4f$ electron states provide large magnetic moment ($7.6 \mu_B$) crystal field effect and strong magnetic interaction which hosts the more rich magnetic states leading to our observed novel transport properties. The further investigation for detailed magnetic structures at various temperatures and fields is necessary and expected to reveal these exotic states.

**SUMMARY**

We systematically studied the transport properties of kagome magnet TmMnAsSn6. The observed prominent topological Hall effect in a wide temperature region suggests a

![Figure 6](image-url)
non-zero spin chirality due to complicated non-collinear magnetic structure with strong fluctuations. In presence of the magnetic transitions, planar transport behavior (especially for PAMR) spanned over various magnetic states can be scaled in School of Physics, Sun Yat-sen University.

We thank Zhongbo Yan in Sun Yat-sen University for useful discussion. Work are supported by National Natural Science Foundation of China (NSFC) (Grants No.U213010013, 92165204, 11904414, 12174454), Guangdong Basic and Applied Basic Research Foundation (Grant No. 2022A1515010035, 2021B1515120015), open research fund of Songshan Lake materials Laboratory 2021SLABFN11, OEMT-2021-PZ-02, National Key Research and Development Program of China (No. 2019YFA0705702), and Physical Research Platform (PRP) in School of Physics, Sun Yat-sen University.

FIG. 7. (a) The PHE $\rho^\parallel_2(0)$ at 10 K, 20 K, 50 K, 100 K, 150 K, 200 K with $\mu_0H=14$ T. (b) Angular dependence of $\Delta\rho^\parallel_2(0) = \rho^\parallel_{20}(0) - \rho^\parallel_{2\theta}(0)$ at 10 K, 20 K, 50 K, 75 K, 100 K, 150 K, 200 K with $\mu_0H=14$ T. The black dash lines are fitting curve. (c) The PHE $\rho^\parallel_2(\mu_0H^wa)$ as a function of $\mu_0H^wa = \mu_0H\sin\theta$ at 10 K, 20 K, 50 K, 100 K, 150 K, 200 K with $\mu_0H=14$ T. (d) $\Delta\rho^\parallel_2(0)$ as a function of $\mu_0H^wa$ at 10 K, 20 K, 50 K, 75 K, 100 K, 150, K, 200 K with $\mu_0H=14$ T.
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