**Rapid Communications**

# Anomalous transverse response of $Co_2MnGa$ and universality of the room-temperature $\alpha_{ij}^A/\sigma_{ij}^A$ ratio across topological magnets

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(Received 16 March 2020; accepted 28 April 2020; published 12 May 2020)

The off-diagonal (electric, thermal, and thermoelectric) transport coefficients of a solid can acquire an anomalous component due to the nontrivial topology of the Bloch waves. We present a study of the anomalous Hall effect (AHE), anomalous Nernst effect (ANE), and thermal Hall effect in the Heusler-Weyl ferromagnet $Co_2MnGa$. The anomalous Wiedemann-Franz law, linking electric and thermal responses, was found to be valid over the whole temperature window. This indicates that the AHE has an intrinsic origin and the Berry spectrum is smooth in the immediate vicinity of the Fermi level. We extract $\alpha_{ij}^A$ from our ANE data and find that the $\alpha_{ij}^A/\sigma_{ij}^A$ ratio approaches $k_B/e$ at room temperature. Scrutinizing all topological magnets previously explored, we observe that this ratio is a sizable fraction of $k_B/e$ at room temperature. We provide a rough explanation for this feature by arguing that the two anomalous transverse coefficients depend on universal constants, the Berry curvature averaged over a window set by either the Fermi wavelength (for Hall) or the de Broglie thermal length (for Nernst). The universal scaling indicates that the widths of the two windows approaches each other at room temperature.

DOI: 10.1103/PhysRevB.101.180404

The anomalous Hall effect (AHE) [1–3] has thermoelectric and thermal counterparts, which emerge whenever the longitudinal electric field is replaced by a longitudinal temperature gradient. When intrinsic, the anomalous Nernst (ANE) and the anomalous Righi-Leduc effect [(ARLE) or anomalous thermal Hall effect], such as AHE, are caused by the nonvanishing Berry curvature of Bloch waves in the host solid [4–8]. A recent theme of interest is the magnitude of these anomalous coefficients. Universal scaling between the amplitudes of magnetization and the amplitude of the transverse response has been sought and invalidated [4,7,9]. Correlations among anomalous transverse coefficients themselves have also been explored. The anomalous version of the Wiedemann-Franz (WF) law, establishing a link between the magnitude of AHE and ARLE has been tested [6,10,11], and the validity of the Mott's relation linking AHE and ANE has been investigated [6,7,12–14].

In this Rapid Communication, we present an extensive study of the three anomalous transport coefficients of $Co_2MnGa$ and report on several new findings. First of all, we find that the anomalous WF law holds in this system between 15 and 300 K. To the best of our knowledge, this is a case of such an extensive verification. Second, we quantify $\alpha_{ij}^A$ and confirm that, as noted previously [8,9], $\alpha_{ij}^A$ is exceptionally large in this system. We quantify the temperature dependence of the $\alpha_{ij}^A/\sigma_{ij}^A$ ratio and find that it tends to saturate to a sizable fraction of $k_B/e$ at high temperatures. We then show that the ratio of $\alpha_{ij}^A/\sigma_{ij}^A$ at room temperature in all known topological magnets lies between 0.2 $k_B/e$ and 0.9 $k_B/e$ despite a hundredfold variation in the amplitude of $\alpha_{ij}^A$. We will see below that such a striking correlation is expected when the anomalous transverse response is intrinsic. It implies that the large $\alpha_{ij}^A$ in this system [8,9] is unsurprising given its large $\sigma_{ij}^A$.

$Co_2MnGa$ is a Weyl ferromagnet [8,15] with a Heusler $L2_1$ structure. It has a Curie temperature of $T_C \approx 694$ K and a saturation moment of $4\mu_B$ per formula unit [16]. Previous studies have reported on strain-induced magnetic anisotropy [17] and negative anisotropic magnetoresistance [18]. Recently, a large anomalous Hall conductivity exceeding 1000 $\Omega^{-1}\,cm^{-1}$ has been observed in thin films and more than 2000 $\Omega^{-1}\,cm^{-1}$ in crystals of $Co_2MnGa$ [8,19,20]. A large anomalous Nernst effect was also reported by a number of previous authors [8,9,14,21]. The magnitude of room-temperature ANE in crystals was found to be remarkably large [8,9]. Guin *et al.* [9] reported that $S_{xy}^A$ is much larger than what is expected according to a simple scaling with magnetization and Sakai *et al.* invoked a quantum critical scaling for $\alpha_{xy}^A$ [8]. In this context, and as we will see below, a comparison of $\alpha_{ij}^A/\sigma_{ij}^A$ across various magnets is illuminating. Despite the fact that

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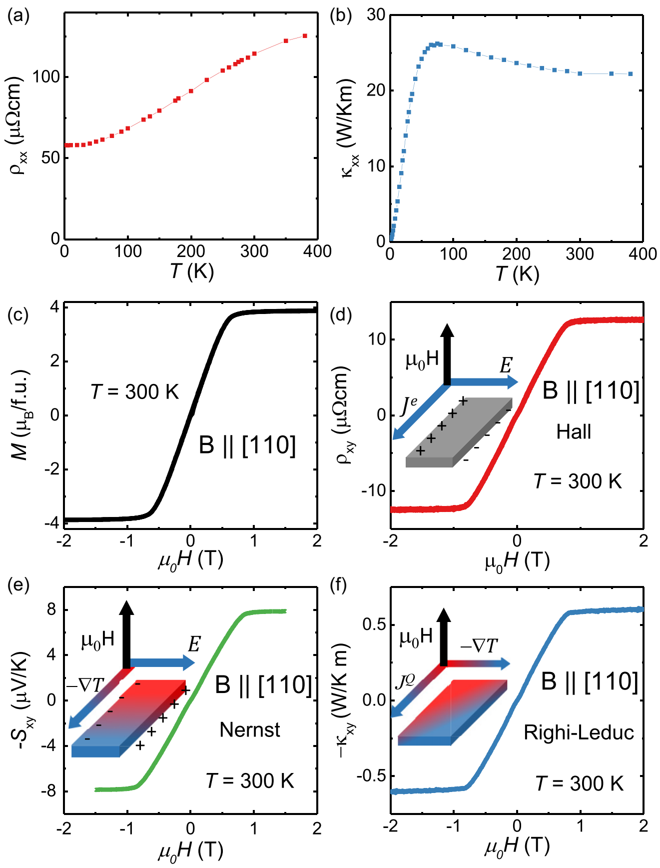


FIG. 1. Basic transport and anomalous transverse responses at ($T = 300$ K) in $Co_2MnGa$: Temperature dependence of (a) electric and (b) thermal conductivity. (c) Magnetization $M$ at room temperature. (d) Anomalous Hall effect, (e) anomalous Nernst effect, and (f) anomalous thermal Hall effect at room temperature. In all cases in this Rapid Communication, $B \parallel [110]$, $I \parallel [001]$. The insets in (d)–(f) show the experimental configurations for Hall, Nernst, and thermal Hall measurements.

$\sigma_{ij}^A$ varies hundredfold (8–1000 $\Omega^{-1}\,\text{cm}^{-1}$) in different topological magnets, the ratio of $\alpha_{ij}^A/\sigma_{ij}^A$ remains a sizable fraction of $k_B/e$.

Figures 1(a) and 1(b) show the temperature dependence of the thermal conductivity $\kappa_{xx}$ and electric resistivity $\rho_{xx}$. Resistivity varies from 125 $\mu\Omega\,\text{cm}$ at room temperature to 60 $\mu\Omega\,\text{cm}$ at low temperatures. This implies a short mean free path for electrons and given the magnitude of $\kappa_{xx}$ a dominant role for phonons (and eventually magnons) in longitudinal thermal transport.

As seen in Fig. 1(c), room-temperature magnetization saturates to 4 $\mu_B$/f.u. similar to what was reported previously [8,19]. In contrast to other topological magnets [6,10,13], no clear hysteresis loop is visible, indicating that the domain walls smoothly propagate without pinning when the magnetic field is swept. The field dependence of the Hall, Nernst, and Righi-Leduc effects at room temperature are shown in Figs. 1(d)–1(f). They all display a behavior similar to the magnetization. The presence of a large anomalous component is visible. The steep initial slope is replaced by a much smaller one at higher magnetic field. The anomalous component of the Hall resistivity ($\simeq$13 $\mu\Omega\,\text{cm}$) is slightly below what was previously reported ($\simeq$15 $\mu\Omega\,\text{cm}$) [8] and the anomalous Nernst signal ($\simeq$8 $\mu$V/K) is somewhat larger than a previous report ($\simeq$6.5 $\mu$V/K) [8]. We note that the room-temperature anomalous $S_{xy}^A$ in crystals [8,9] is three to four times larger than in thin films [14,21].

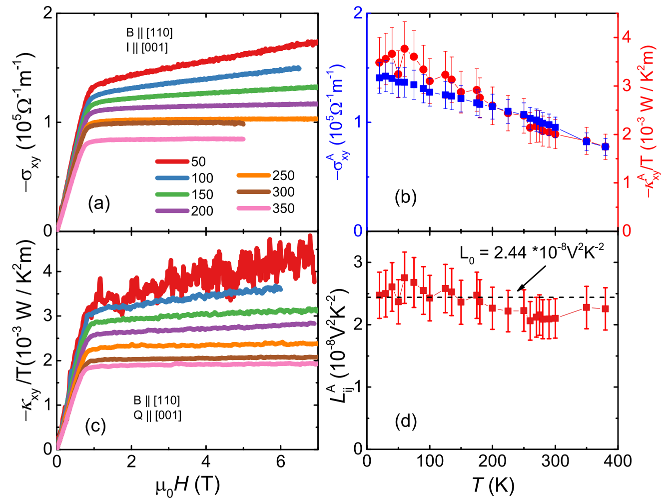


FIG. 2. Temperature evolution of Hall conductivity, thermal Hall conductivity, and anomalous transverse Lorenz number in $Co_2MnGa$: (a) and (b) Field-dependent Hall conductivity $\sigma_{xy}$ and transverse thermal conductivity divided by $T$ $\kappa_{xy}/T$ at selected temperatures. (c) Temperature-dependent anomalous Hall conductivity and transverse thermal conductivity. (d) The anomalous transverse Lorenz ratio ($L_{xy}^A = \kappa_{xy}^A/\sigma_{xy}^A T$).

Figures 2(a) and 2(c) show the thermal evolution of the Hall conductivity ($\sigma_{xy}$) and the thermal Hall conductivity ($\kappa_{xy}/T$) in a field window extended to 7 T (the raw data can be seen in the Supplemental Material [22]). In both cases, given the clear change in the slope of the curve, the extraction of the anomalous components is straightforward. Figure 2(b) shows how the anomalous Hall conductivity $\sigma_{xy}^A$ and the anomalous thermal Hall conductivity $\kappa_{xy}^A/T$ depend on temperature. Both increase almost twofold as the system is cooled from 300 to 15 K. The validity of the anomalous WF law for transverse response can be checked by comparing the anomalous Lorenz number $L_{xy}^A = \frac{\kappa_{xy}^A}{T\sigma_{xy}^A}$ with the Sommerfeld value $L_0 = \frac{\pi^2}{3}(\frac{k_B}{e})^2$ where $k_B$ and $e$ are the Boltzmann constant and the elementary charge of an electron. As seen in Fig. 2(d), within the experimental margin, we find that $L$ remains close to $L_0$ and the anomalous WF law is verified.

In Fig. 3(a), we compare the evolution of the anomalous Lorenz number $L_{ij}^A$ in $Co_2MnGa$ with those found in two other topological magnets. In the case of $Mn_3Sn$ [6], the anomalous WF law was found to be held above 150 K. The commensurate triangular magnetic order is taken over by a helical one below this temperature. In $Mn_3Ge$ [10], such a transition is absent, and thus, the validity of the anomalous WF law could be checked down to cryogenic temperatures, but a sizable difference between $L_{xy}^A$ and $L_0$ was observed above 100 K and attributed to a mismatch between thermal and electrical summations of the Berry curvature [10]. In common elemental ferromagnets, such as Ni [26] and Fe [6], $L_{xy}^A$ was found to be close to $L_0$ at low temperatures, and

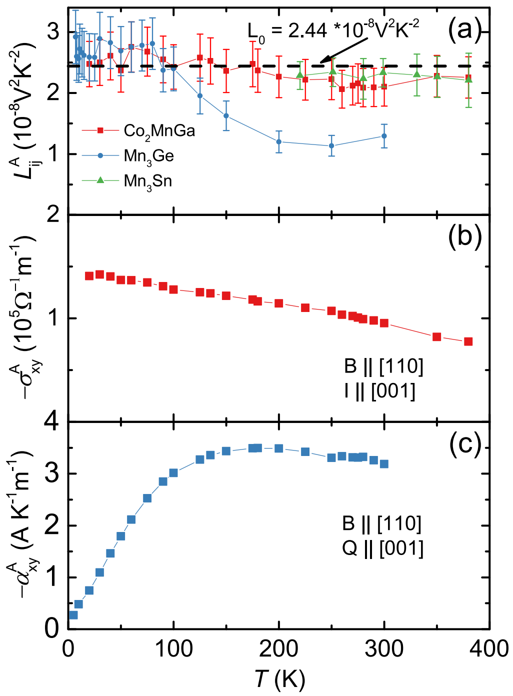


FIG. 3. Anomalous transverse coefficients: (a) The anomalous Lorenz number $L^A_{xy} = \kappa^A_{xy}/T\sigma^A_{xy}$ remains close to the Sommerfeld value of $L_0$. The anomalous Lorenz number of $Mn_3Sn$ [6] and $Mn_3Ge$ [10] are also shown. The dashed horizontal line represents $L_0$. (b) The anomalous Hall conductivity $\sigma^A_{xy}$ as a function of temperature. (c) The anomalous transverse thermoelectric conductivity $\alpha^A_{xy}$ as a function of temperature. For comparison with data reported previously [8,9], see the Supplemental Material [22].

a downward deviation emerges on heating, presumably due to inelastic scattering [6]. Thus, $Co_2MnGa$ is the first case of a magnet in which the anomalous WF law remains valid between 15 and 300 K. This means that not only inelastic scattering is irrelevant, but also the thermal and electrical summations of the Berry curvature match each other. Thus, the variation of the Berry curvature near the Fermi energy is not abrupt in contrast to the case of $Mn_3Ge$ [10].

Figures 3(b) and 3(c) show the temperature dependence of $\sigma^A_{xy}$ and $\alpha^A_{xy}$. The magnitude of $\sigma^A_{xy}$ (which attains 1400 $\Omega^{-1}\,cm^{-1}$ at 2 K and decreases to 1000 $\Omega^{-1}\,cm^{-1}$ at room temperature) is remarkably large and in reasonable agreement with previous studies [8,9]. The anomalous transverse thermoelectric conductivity, $\alpha^A_{xy}$ displays a nonmonotonous temperature dependence decreasing only below 150 K and vanishing as expected in the zero-temperature limit. Our $\alpha^A_{xy}$ data are in reasonable agreement with the data of Sakai and co-workers [8] but do not match what was reported by Guin *et al.* [9]. As discussed in the Supplemental Material [22], this is due to an elementary mistake in manipulating the sign of the two components of $\alpha^A_{xy}$. Rectifying this mistake, one finds that the three sets of data give a comparable value at room-temperature in the Supplemental Material [22].

The low-temperature slope of $\alpha^A_{xy}$ can be quantified by plotting $\alpha^A_{xy}/T$ as a function of temperature in the Supplemental Material [22]. According to Mott's relation, this slope quantifies the variation of the low-temperature $\sigma^A_{xy}$ caused by an infinitesimal shift in the chemical potential. The magnitude of the extracted slope in $Co_2MnGa$ ($\alpha^A_{xy}/T \simeq -0.037 AK^{-2}\,m^{-1}$) is smaller than what was seen in $Co_3Sn_2S_2$ [13]. In the latter case, the extracted slope was found to be in good agreement with the observed variation of low-temperature $\sigma^A_{xy}$ caused by a small shift in the chemical potential [13]. Our data reveal a well-defined $\alpha^A_{xy}/T$ and merge to the $-\ln T$ behavior above 100 K as reported by a previous study [8]. (See the discussion in the Supplemental Material [22].)

We now turn our attention to the magnitude of the $\alpha^A_{ij}/\sigma^A_{ij}$ ratio. In Fig. 4(a), we present the temperature dependence of this ratio in $Co_2MnGa$ and compare it to the available data of other magnets. Among these five systems, $Co_3Sn_2S_2$ distinguishes itself by the sign change in $\alpha^A_{xy}$ around 60 K [13]. However, like the four other systems, this ratio tends towards saturation at a value which is a sizable fraction of $k_B/e$.

As seen in Fig. 4(b), even though $\sigma^A_{ij}$ changes by a factor of 100 among different magnetic materials, the room-temperature $\alpha^A_{ij}/\sigma^A_{ij}$ ratio remains between $k_B/5e$ and $k_B/e$, which is the natural units of the ratio of these two quantities. This observation begs an explanation within our present understanding of anomalous transverse coefficients caused by Berry curvature.

The following expressions link the anomalous Hall and the anomalous thermoelectric conductivities to the Berry curvature $\Omega^z$:

$$\sigma^A_{xy} = \frac{e^2}{\hbar}\int_{BZ}\frac{d^3k}{(2\pi)^3}f(k)\Omega^z, \quad (1)$$

$$\alpha^A_{xy} = \frac{ek_B}{\hbar}\int_{BZ}\frac{d^3k}{(2\pi)^3}s(k)\Omega^z. \quad (2)$$

Here, $f(k)$ is the Fermi-Dirac distribution and $s(k) = -f(k)\ln([(k)] - [1-f(k)]\ln[1-f(k)]$ is the (von Neumann) entropy density of electron gas, which are plotted in Figs. 4(c) and 4(e). These Fermi-sea expressions for $\sigma^A_{xy}$ and $\alpha^A_{xy}$ have Fermi-surface counterparts where the pondering factors are $\partial f/\partial\epsilon$ and $\partial s/\partial\epsilon = \frac{\partial f}{\partial\epsilon}\frac{(\epsilon-\mu)}{k_BT}$ (see the Supplemental Material [22] for a discussion on the equivalency between the two formalisms).

Equation (1) implies that the anomalous Hall conductivity is an average of the Berry curvature over the occupied fermionic states. One can express this idea by writing [13]: $\sigma^A_{xy} \approx \frac{e^2}{\hbar}\frac{1}{c}\langle\frac{\Omega_B}{\lambda_F^2}\rangle$, where $\lambda_F$ is the Fermi wavelength on the plane perpendicular to the magnetic field and $c$ is the lattice parameter along the magnetic field. In contrast, Eq. (2) implies that $\alpha^A_{xy}$ averages the Berry curvature over the states, which have a finite entropy, which are within a thermal thickness of the Fermi level. Therefore, $\alpha^A_{xy} \approx \frac{ek_B}{\hbar}\frac{1}{c}\langle\frac{\Omega_B}{\Lambda^2}\rangle$ [13], where $\Lambda = \sqrt{\frac{h^2}{2\pi mk_BT}}$ is the de Broglie thermal wavelength on the plane perpendicular to the magnetic field. According to these expressions, $\alpha^A_{xy}$ vanishes in the low-temperature limit because $\Lambda$ will diverge. On the other hand, $\lambda_F$ and, therefore, $\sigma^A_{xy}$ are expected to be finite in the whole temperature range. Now, $\alpha^A_{xy}/\sigma^A_{xy}$ will be set by $\frac{k_B}{e}\langle\frac{\lambda_F^2}{\Lambda^2}\rangle$. Therefore, as the system is warmed up, $\lambda_F$ and $\Lambda$ become comparable in size,

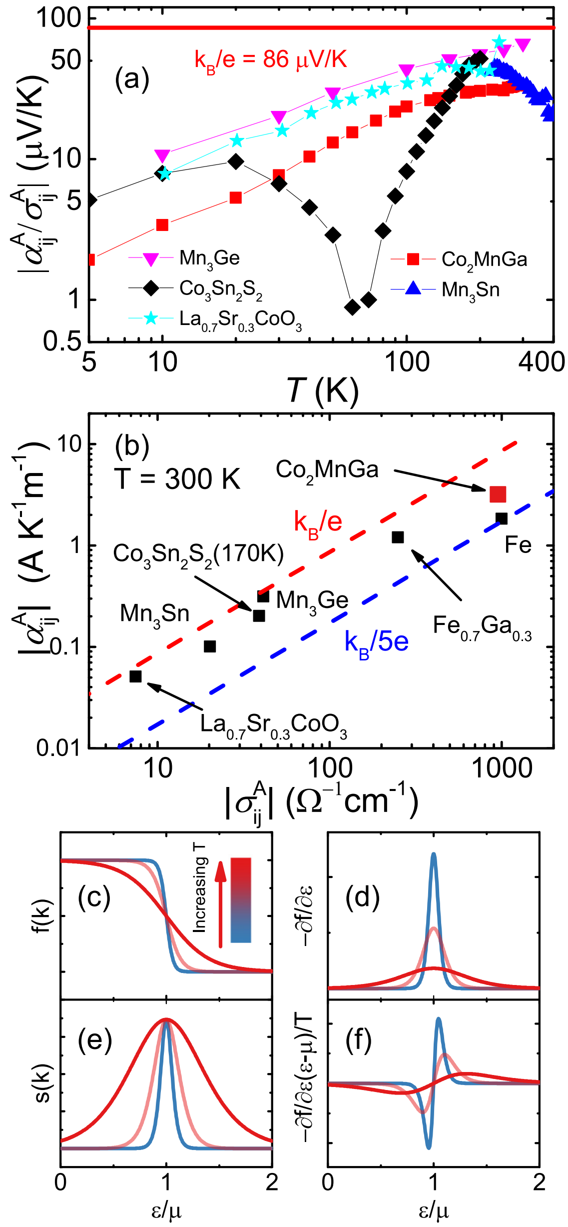


FIG. 4. The universal relation found in the $\alpha_{ij}^A/\sigma_{ij}^A$ ratio and the pondering functions: (a) The $\alpha_{ij}^A/\sigma_{ij}^A$ ratio as a function of temperature in different magnets including $Mn_3Sn$ [6], Fe [6], $Mn_3Ge$ [10], $La_{0.7}Sr_{0.3}CoO_3$ [27], and $Co_3Sn_2S_2$ [13]). $k_B/e$ is represented by a red solid line. (b) Room-temperature $\alpha_{ij}^A/\sigma_{ij}^A$ in different magnets ($Fe_{0.7}Ge_{0.3}$ [28]). All the points are shown at 300 K ($Co_3Sn_2S_2$ is taken at 170 K because of the magnetic order). They lie all between $k_B/5e$ (blue line) and $k_B/e$ (red line). Note the range of $\sigma^A$ between 8 and 1000 $\Omega^{-1}$ cm$^{-1}$. (c)–(f) Pondering functions in the Fermi sea (c) and (e) and the Fermi surface (d) and (f) expressions of the anomalous Hall coefficients. (c) Fermi-Dirac distribution $f(k)$ used for Fermi-sea $\sigma_{ij}^A$. (d) Its energy derivative, used for Fermi-surface $\sigma_{ij}^A$. (e) The entropy density of electrons $s(k)$, used for Fermi-sea $\alpha_{ij}^A$. (f) Its energy derivative, used for Fermi-surface $\alpha_{ij}^A$.

the ratio should approach $k_B/e$. This is admittedly a handwaving explanation. We expect that the correlation between the magnitudes of $\sigma_{ij}^A$ (300 K) and $\alpha_{ij}^A$ (300 K) in all known topological magnetic systems stimulates a rigorous theoretical investigation.

Let us note that associating $\alpha_{ij}^A$ and $\Lambda$ explains why the magnitude of the anomalous Nernst effect ($S_{ij}^A$) in a given magnet anticorrelates with the mean free path [13], whereas the ordinary Nernst effect correlates with the mean free path [29]. The intrinsic anomalous $\alpha_{ij}^A$ (such as the intrinsic anomalous $\sigma_{ij}^A$) should not depend on the mean free path but on the average Berry curvature. In contrast, semiclassical $\alpha_{ij}$ and $\sigma_{ij}$ both scale with the inverse of the square of the mean free path [29].

The large anomalous thermoelectric response of $Co_2MnGa$ is demystified by this approach. The room-temperature $\alpha_{xy}^A$ of 3 A K$^{-1}$ m$^{-1}$ is large compared to other topological magnets with lower AHE. Interestingly, bcc iron, whose room-temperature AHE is only slightly lower ($\simeq$1000 $\Omega^{-1}$ cm$^{-1}$ [6,30]) has a room-temperature $\alpha_{xy}^A$ as large as 2 A K$^{-1}$ m$^{-1}$ [6]. Thus, our observation implies that knowing $\sigma_{ij}^A$ allows one to predict the order of magnitude of $\alpha_{xy}^A$. Such scaling relations are well known in the context of ordinary transport coefficients, such as the $T^2$ resistivity prefactor [31] or low-temperature slope of the Seebeck coefficient [32].

To summarize, we studied the anomalous off-diagonal coefficients of $Co_2MnGa$ and checked the validity of the anomalous transverse Wiedemann-Franz law in the whole temperature range. We quantified $\alpha_{xy}^A$ and found that, in all known topological magnets, its magnitude at room temperature scales with the size of the anomalous Hall conductivity and proposed an explanation for this observation, based on Haldane's conjecture [33] that the anomalous transverse response is fundamentally a Fermi-surface property.

This work was supported by the National Science Foundation of China (Grants No. 51861135104 and No. 11574097), the National Key Research and Development Program of China (Grant No. 2016YFA0401704), the Fundamental Research Funds for the Central Universities (Grant No. 2019kfyXMBZ071) in China, by Agence Nationale de la Recherche (Grant No. ANR-18-CE92-0020-01) in France, by CREST (Grant No. JPMJCR18T3), Japan Science and Technology Agency, by Grants-in-Aids for Scientific Research on Innovative Areas (Grants No. 15H05882 and No. 15H05883) from the Ministry of Education, Culture, Sports, Science, and Technology of Japan, and by Grants-in-Aid for Scientific Research (Grant No. 19H00650) from the Japanese Society for the Promotion of Science (JSPS). Z.Z. was supported by the 1000 Youth Talents Plan, and K.B. was supported by the China High-End Foreign Expert Program. L.X. acknowledges a Ph.D. scholarship by the China Scholarship Council (CSC). B.F thanks the support of JEIP-Collège de France.

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