Planar Hall effect as a sign of chiral magnetic anomaly in half-Heusler antiferromagnet DyPdBi

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We show that half-Heusler phase DyPdBi, which is superconducting below 0.9 K and antiferromagnetic below \( \approx 3 \) K, displays at higher temperatures very large negative longitudinal magnetoresistance and planar Hall effect, both reflecting the presence of chiral magnetic anomaly. We ascribe these properties, being hallmark features of topological semimetals, to the existence of massless Weyl fermions within electron band structure of this compound.

I. INTRODUCTION

In recent years, topological semimetals have been in the spotlight of condensed matter physics, and this is because of their exciting electrical transport behaviors, which open new perspectives for real-world applications (quantum computing, spintronics, etc.) \[1,2\]. The group comprises a large variety of materials bearing Dirac or Weyl fermions, which exhibit exotic quantum mechanical phenomena at easily accessible temperatures and magnetic fields \[3\]. In particular, Weyl semimetal (WSM) is distinguished by the presence of Weyl nodes, contact points between two or more bands, always occurring in pairs with opposite chirality and behaving like magnetic monopoles \[4,5\]. Low-energy excitations in WSM are massless Weyl fermions, and surface states of them form specific Fermi arcs in momentum space. Such unusual electronic band structure of WSM gives rise to uncommon electron transport properties. One of them is the Adler-Bell-Jackiw effect, known also as chiral magnetic anomaly (CMA) \[6–8\]. CMA arises when electric field is parallel to magnetic field and manifests itself as negative longitudinal magnetoresistance caused by electron pumping between two Weyl nodes of opposite chirality \[4\]. The appearance of CMA was reported for several topological semimetals, like TaAs \[9\], GdPtBi \[10,11\], \[4\]. The latter compound belongs to an outstanding group of multifunctional materials called half-Heusler (HH) phases. Several HH bismuthides bearing rare earth elements were theoretically predicted to exhibit topologically nontrivial character \[20\], which may coexist at low temperatures with superconductivity and/or antiferromagnetic ordering. Examples of superconducting materials considered as putative topological insulators or WSMs are nonmagnetic compounds YPtBi, LuPtBi, and LuPdBi \[21,20\]. In turn, the HH phases RPdBi (\( R = \text{Sm, Dy, Ho, Er, Tm} \)) were found to be antiferromagnetic superconductors that show in parallel features of Dirac or Weyl states \[27,30\]. Recently, particular attention was devoted to antiferromagnetic and non-superconducting compound GdPtBi, which was acclaimed as the first WSM with Weyl nodes induced by magnetic field \[10\]. Apart from manifesting large CMA \[10,11\], it was shown to display strong anomalous Hall effect \[31\] accompanied by huge PHE \[19\].

In this paper we report the electrical transport properties of single-crystalline DyPdBi, another representative of the group of HH bismuthides. Polycrystalline samples of this compound were reported to order antiferromagnetically below Néel temperature \( T_N \) of 3.5 K \[32\], whereas investigations of single crystals revealed \( T_N = 2.7 \) K \[29\] or \( T_N = 3.7 \) K \[33\]. The magnetic structure was determined by neutron diffraction to be characterized by the propagation vector (1/2, 1/2, 1/2) \[29,34\], alike that of GdPtBi \[35\]. In the antiferromagnetically ordered state, namely below 0.9 K, DyPdBi becomes superconducting.

Motivated by the similarities between GdPtBi and DyPdBi, we carried out comprehensive measurements of the magnetotransport in the latter material, with emphasis on properties related to CMA. Obtained data hint at its topologically nontrivial character and allow to conclude that also DyPdBi is a Weyl semimetal.

II. EXPERIMENTAL DETAILS

Single crystals of DyPdBi were grown from Bi flux and characterized as reported before \[33\]. Cuboid samples suitable for electrical transport measurements were cut along (100) crystallographic directions from single crystals oriented using backscattering Laue method (see Supplemental Material \[36\] for a typical Laue diffraction pattern). Electrical contacts were made with 50 µm silver wire attached to the samples with silver paint.

Electrical transport measurements were performed using conventional four-probe method in temperature range
FIG. 1. Magnetoresistance of DyPdBi measured as a function of magnetic field strength in temperature range from 10 K to 300 K in (a) transverse and (b) longitudinal configuration of electrical current and magnetic field. Inset to panel (a) shows schematically the measurement configuration.

10–300 K and in magnetic fields up to 14 T employing a Quantum Design PPMS platform. The experimental data were either symmetrized or antisymmetrized in order to dispose of contacts misalignment effect.

III. RESULTS AND DISCUSSION

A. Magnetoresistance

Figures 1(a) and 1(b) present the magnetoresistance (MR ≡ [ρ(B)−ρ(B=0)]/ρ(B=0)) of single-crystalline DyBdBi measured at several temperatures from the range 10–300 K in transverse (TMR; magnetic field $B$ perpendicular to the current $j$ flowing along the crystallographic $a$-axis) and longitudinal (LMR; $B \parallel j \parallel a$) configuration, respectively. In weak magnetic fields, TMR rapidly grows with increasing $B$. Similar behavior was observed in a few HH phases and ascribed to weak antilocalization effect [24, 25, 30, 37–39]. At certain values of $B$, the magnetoresistance attains maximum, then monotonically decreases, becomes negative and reaches in $B = 14$ T fairly large values ($\approx -70\%$ at $T = 10$ and 25 K). With increasing temperature, the field variations of TMR become less pronounced and at $T \geq 200$ K it is positive in the entire magnetic field range covered. At $T = 300$ K and in $B = 14$ T, TMR = 25%, which is a fairly large value. Classical TMR due to Lorentz force, is positive [40]. Negative TMR was observed in ferromagnetic systems which exhibit metal-insulator transition [41], in strongly disordered nonmagnetic narrow-gap systems [42], but also in a few HH phases [30, 43–46]. In the case of YbPtBi [44, 45], it could be naturally attributed to Kondo effect [47]. In turn, negative TMR found for HH antimonides [48] and for HoPdBi [39] was explained by considering reduction in spin-disorder scattering due to alignment of magnetic moments by magnetic field, as described by de Gennes and Friedel [48]. It seems that similar mechanism can be appropriate also in DyPdBi (see Supplemental Material [36] for fits of the de Gennes–Friedel formula to the resistivity measured in transverse magnetic field). Alternatively, negative TMR in this compound may arise from reconstruction of electronic band structure in external magnetic field, as proposed for GdPtBi [10]. Very large density of spin-down states at the Fermi level calculated for DyPdBi [49], would facilitate such a mechanism.

As can be inferred from Fig. 1(b), LMR of DyPdBi is negative up to $T = 200$ K and significantly larger than TMR measured at the same temperatures (at 10 K and in field of 14 T, the difference is almost double). It is worth noting that absolute limit of negative value of MR is -100% (such value would mean that magnetic field suppresses the resistivity completely, like in quantum Hall systems), so LMR values of about -80% found for DyPdBi are really huge.

FIG. 2. Difference between longitudinal conductivity and transverse conductivity as a function of magnetic field, obtained for DyPdBi at several different temperatures. Red solid lines represent the fits with $(σ_∥ − σ_⊥) ∝ B^2$ function.
Since de Gennes–Friedel effect on scattering is isotropic, one can ascribe the large difference in the magnitude of MR measured at the two principal configurations to the presence of CMA. Fig. 2 shows the magnetic field dependence of differences between the longitudinal conductivity, $\sigma_\parallel$, and the transverse conductivity, $\sigma_\perp$, obtained for several different temperatures. Such a subtraction makes possible to dispose the isotropic contribution to MR due to de Gennes–Friedel effect, and hence the resulting difference can be considered as the contribution from CMA. According to theoretical predictions \[8\], when the chiral anomaly takes place, the electrical conductivity makes possible to dispose the isotropic contribution to CMA. According to theoretical predictions \[8\], when the chiral anomaly takes place, the electrical conductivity, $\sigma$ (in longitudinal field should be proportional to $B^2$. Indeed, such dependence was found for several compounds demonstrating CMA, e.g. ZrTe$_5$ \[12\] and GdPtBi \[11\]. The result of fitting the experimental data of DyPdBi to $B^2$ function is shown as red solid lines in Fig. 2. Another theoretical model proposed recently \[54\], predicts that CMA can lead to $(\sigma_\parallel - \sigma_\perp) \propto B^{3/2}$. In the case of DyPdBi, the latter model suits definitely worse that the former one (see Supplemental Material \[36\] for comparison of the corresponding fits).

### B. Angle dependent magneto-resistance

Figure 3(a) presents the angular magnetic field dependence of the electrical resistivity of DyPdBi, $\rho(\theta)$ measured with $j \parallel a$-axis in $B = 14$ T, at temperatures from 10 to 300 K. The observed strong variations of $\rho(\theta)$ are quite unusual for a paramagnet ($T_N$ of DyPdBi equals 3.7 K). This feature is even better visualized in Fig. 3(b), where the anisotropic magnetoresistance (AMR = $(\rho(\theta) - \rho_\perp)/\rho_\perp$) isotherms are presented ($\rho_\perp$ is the electrical resistivity measured in transverse field, i.e. for $\theta = 0^\circ$). AMR is a common property of ferromagnetic materials \[51\], for which it is usually positive, with the exception of very few systems \[52\] \[53\]. In contrast, DyPdBi demonstrates giant negative AMR at the entire temperature range studied. Its amplitude decreases with increasing temperature but even at $T = 300$ K it is as large as about -17%.

In nonmagnetic materials, AMR can be due to anisotropy of the Fermi surface or due to topologically nontrivial nature of their electronic structure. In the latter case, large AMR results from change in the sign of the magnetoresistance with varying $\theta$ from positive in the transverse configuration to negative in the longitudinal configuration \[8\] \[10\] \[11\]. According to the theory $\rho(\theta)$ of topological semimetal should behave in the same manner as for a ferromagnet, i.e. $\rho(\theta) = \rho_\parallel - (\rho_\perp - \rho_\parallel) \cos^2 \theta$, where $\rho_\parallel$ is electrical resistivity measured in longitudinal field \[8\]. It should be noted, however, that this expression was derived for polycrystalline ferromagnets and does not take into account magnetocrystalline anisotropy \[54\].

In order to qualitatively analyze the experimental $\rho(\theta)$ dependencies of DyPdBi, the following equation appropriate for single crystals with cubic symmetry \[55\] \[57\] was applied:

$$\rho(\theta) = \rho_0(1 + A_2 \cos 2\theta + A_4 \cos 4\theta + A_8 \cos 8\theta + ...). \quad (1)$$

The obtained fits are shown by red solid lines in Fig. 3(a), and the fitting parameters are listed in Table I. Equation 1 describes $\rho(\theta)$ very well. The $\cos 2\theta$ term alone perfectly describes the experimental angular dependence at high temperatures, from 300 K down to 150 K (note that it is equivalent to the mentioned above function containing $\cos^2 \theta$). At 75 K the $\cos 4\theta$ contribution is necessary to reproduce four-fold-symmetry features in $\rho(\theta)$, at 25 and 10 K there are eight-fold features, well accounted for by the $\cos 8\theta$ term in Eq. 1.

Similarly complex behavior of $\rho(\theta)$ was found before for thin films of ferromagnetic semiconductors \[56\] \[57\], and most recently also for single-crystalline GdPtBi \[19\].

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**Figure 3.** (a) Angular dependence of the electrical resistivity of single-crystalline DyPdBi measured with $j \parallel a$-axis at several different temperatures in $B = 14$ T. Red lines correspond to the fits with Eq. 1. (b) AMR isotherms derived from data shown in panel (a).
FIG. 4. (a) Angular dependence of the planar Hall effect measured for single-crystalline DyPdBi at \( T = 10 \) K in several constant magnetic fields. The measurement geometry is shown in the inset. (b) Angular dependence of PHE in single-crystalline DyPdBi measured as in panel (a) in constant magnetic field \( B = 14 \) T at several different temperatures. Red solid lines in both (a) and (b) represent the fits of the function \( \rho_{\text{PHE}} = \Delta \rho \sin(\phi) \cos(\phi) \). (c) Hall resistivity of single-crystalline DyPdBi measured as a function of magnetic field direction at \( T = 10 \) K and in \( B = 14 \) T. The measurement geometry is shown in the inset. (d) Field dependence of chiral resistivity of DyPdBi obtained from the fits shown in panel (a).

TABLE I. Parameters obtained from the fitting of Eq. 1 to the experimental \( \rho(\theta) \) data of DyPdBi. All \( A_4 \) and \( A_8 \) values shown as zeros were smaller than \( 2 \times 10^{-4} \).

| \( T \) (K) | \( \rho_0 \) (mΩ cm) | \( A_2 \) | \( A_4 \) | \( A_8 \) |
|--------|-----------------|------|------|------|
| 10     | 0.234           | 0.364| 0.245| 0.065|
| 25     | 0.453           | 0.267| 0.139| 0.019|
| 75     | 1.496           | 0.199| 0.032| 0    |
| 150    | 1.638           | 0.162| 0    | 0    |
| 200    | 1.182           | 0.133| 0    | 0    |
| 300    | 0.629           | 0.094| 0    | 0    |

C. Planar Hall effect

Figure 4 presents the results of PHE measurements performed for DyPdBi with magnetic field applied parallel to the sample surface, and the sample was rotated in such way that the field was always in-plane (see the inset to Fig. 4(a)).

According to the theory [14, 58], planar Hall resistivity, \( \rho_{\text{PHE}} \), of ferromagnets or topological semimetals depends on the magnetic field direction as \( \rho_{\text{PHE}}(\phi) = \Delta \rho \sin(\phi) \cos(\phi) \), where \( \Delta \rho = \rho_\perp - \rho_\parallel \) is resistivity anisotropy induced by CMA and \( \phi \) is an angle between current and magnetic field directions. Thus, \( \rho_{\text{PHE}}(\phi) \) should have extrema at \( 45^\circ \), \( 135^\circ \), \( 225^\circ \) and \( 315^\circ \).

It is evident from Fig. 4 that the behavior of PHE in DyPdBi follows the theoretical predictions. It is worth noting that PHE is a direct consequence of AMR [58], and hence, apart from the specific configuration of \( B \) and \( j \), has nothing in common with “usual” Hall effect appearing due to Lorentz force. The difference between these two magnetogalvanic effects is visualized in Fig. 4 where in panel (c) there is shown the angular dependence of the Hall resistivity, \( \rho_{xy} \), of DyPdBi measured at \( T = 10 \) K in magnetic field \( B = 14 \) T aligned perpendicular to the sample surface. \( \rho_{xy}(B) \) is an antisymmetric function of the magnetic field, thus \( \rho_{xy}(\theta) \) has only two extrema (at \( 90^\circ \) and \( 270^\circ \)), whereas \( \rho_{\text{PHE}}(B) \) is symmetric in \( B \).

PHE in DyPdBi is very well described by the \( \Delta \rho \sin(\phi) \cos(\phi) \) expression, and the results of its fitting to the experimental data are shown as red solid lines in Figs. 4(a) and 4(b). The so-obtained values of \( \Delta \rho \) are
FIG. 5. (a) Hall resistivity of single-crystalline DyPdBi measured as a function of magnetic field at several different temperatures with the experimental geometry displayed in Fig. 4(c). Inset shows the temperature dependence of the Hall coefficient at $T = 10$ K. (b) Comparison of temperature dependence of the Hall coefficient $R_H$, and that of $\Delta \rho(T)$ PHE parameter, both determined in magnetic field of 14 T.

plotted as functions of magnetic field and temperature, in Fig. 4(d) and Fig. 5(b), respectively. Both these dependences are nonmonotonic, in contrast to the behavior of $\Delta \rho$ reported for GdPtBi, where $\Delta \rho$ increases with magnetic field and decreases with temperature [19], or that observed for Bi$_2$Sb$_2$Te$_3$, with $\Delta \rho$ also increasing with magnetic field [17]. However, it is worthwhile mentioning that in the latter case $\Delta \rho$ was shown to strongly depend on the Fermi level position, which is fully in line with the theory [14], that predicts distinct dependence of $\Delta \rho$ on the density of states at the Fermi level. Below we show how the nonmonotonic $\Delta \rho(T)$ behavior may also have such origin.

D. Hall effect

It was shown via theoretical calculations [10, 31], that the electronic structure of GdPtBi is strongly affected by applied magnetic field. It seems likely that similar effect occurs for DyPdBi.

To examine this assumption measurements of the Hall resistivity, $\rho_{xy}$, were performed, and the results are displayed in Fig. 5(a). As can be inferred from this figure, $\rho_{xy}$ depends on temperature and field in irregular manner, which implies strong dependence of the electronic band structure of the compound on both $T$ and $B$. Actually, the calculated band structure is fairly complex with several bands crossing the Fermi level. Figure 5 shows the temperature dependence of the Hall coefficient, $R_H = \rho_{xy}/B$, of single-crystalline DyPdBi recorded in $B = 14$ T. $R_H$ significantly increases with increasing $T$ up to about $T = 100$ K, at higher temperatures, it decreases back, reaching at 300 K a value close to that observed at 10 K. The overall $R_H(T)$ variation is very similar to the behavior of $\Delta \rho(T)$ shown in the same Fig. 5(d) for a direct comparison.

In a single-band approximation the Hall coefficient directly reflects the carrier concentration: $n_H = 1/(eR_H)$ ($e$ is elementary charge), thus nonmonotonic $\Delta \rho(T)$ dependence in DyPdBi apparently follows temperature variation of carrier concentration, which is in accord with the theoretical prediction of $\Delta \rho$ being proportional to the density of states at the Fermi level [14]. In Ref. 10 it has been shown that the carrier concentration in GdPtBi monotonically increases with temperature, and this feature is well correlated with the monotonic behavior of its $\Delta \rho(T)$ reported in Ref. 19.

As can be inferred from inset to Fig. 5(a), the Hall coefficient of DyPdBi is strongly dependent on the magnetic field strength. The observed nonmonotonic behavior of $R_H(B)$ can be rationalized by considering nonlinear dependence of the carrier concentration on $B$. This contrasts with the case of GdPtBi, where $\rho_{xy}(B)$ is linearly proportional to $B$ [11].

IV. CONCLUSIONS

The results obtained for high-quality single crystals of DyPdBi revealed giant anisotropic magnetoresistance and large planar Hall effect, which can be ascribed to the chiral magnetic anomaly, a hallmark feature of topological semimetals. The compound exhibits complex behavior of the magnetoresistance isotherms, which do not saturate up to the highest magnetic fields and attain huge negative values at low temperatures, even in transverse measurement geometry. Even at room temperature, AMR of DyPdBi has very large negative values in strong magnetic fields. The amplitude of PHE is also large and depends on temperature and magnetic field in irregular manners, probably due to strongly $T$- and $B$-dependent carrier concentration, as revealed by the Hall effect results. Keeping in mind that the results of
single-band Drude approach yield only the upper limit of real carrier concentration in a multi-band material like DyPdBi, these dependences of carrier concentration provide explanation of the differences in behavior of the PHE amplitudes for DyPdBi and GdPtBi. The obtained data indicate that DyPdBi is a convenient platform for tuning the magnitude of PHE by chemical doping. The presence of AMR and PHE in this material makes it a good candidate for magnetic sensor applications.

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SUPPLEMENTAL MATERIAL
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Laue diffraction

High quality of the single crystal studied was confirmed by backscattering Laue method using a Proto-COS Laue system. An example of the X-ray Laue diffraction pattern is shown in Fig. S1.

![Image](image.png)

**FIG. S1** Laue diffraction pattern of DyPdBi single crystal taken with incident X-ray beam close to the [100] crystallographic direction.

Analysis of magnetoresistance measured in transverse and longitudinal geometries

For the first time, the magnetic field dependence of the electrical resistivity of half-Heusler compounds was interpreted in terms of De Gennes-Friedel function by Karla et al. in Ref. [SR1]. The function can be written as follows:

\[
\rho(B) = \rho_0 \left( 1 - \beta^2 \left( \frac{CB}{T - \theta_{CW}} \right) \right),
\]

where \( C = N\mu^2/k_B \) is Curie constant, \( \theta_{CW} \) is paramagnetic Curie-Weiss temperature and \( \beta \) is Brillouin function. Similar approach to the \( \rho(B) \) data of DyPdBi yielded the results shown in Fig. S2(a) as red solid lines. For example, for the isotherm measured at \( T = 10 \) K the Dy magnetic moment \( \mu = 7.0 \mu_B \) was calculated (assuming \( \theta_{CW} = -14.3 \) K, reported in Ref. [SR2]). The latter value is smaller than the Russel-Saunders free ion value of trivalent dysprosium (\( \mu_{\text{theor}} = 10.64 \mu_B \)), yet close to \( \mu = 8.3 \mu_B \) obtained for DyNiSb from the de Gennes-Friedel function analysis described in Ref. [SR1]. The difference between the theoretical and experimental values of magnetic moment is most likely the effect of crystalline electric field.

Figure S2(b) shows the magnetic field dependence of the difference between longitudinal and transverse electrical conductivity of DyPdBi measured at \( T = 10 \) K and 25 K. The quality of the fit with \( (\sigma_\parallel - \sigma_\perp) \propto B^2 \) (represented by red solid lines) is definitely better than that with \( (\sigma_\parallel - \sigma_\perp) \propto B^{3/2} \) (green lines) for both temperatures.
FIG. S2 (a) Electrical resistivity of DyPdBi measured in transverse geometry (see the main text) as a function of magnetic field at several different temperatures. Red solid lines represent the results of least-squares fitting with de Gennes-Friedel function. (b) Comparison of two different fits to field dependence of the difference between longitudinal and transverse electrical conductivity of DyPdBi measured as described in the main text at $T = 10 \text{K}$ and $25 \text{K}$. Red and green solid lines represent fits with the functions $\propto B^2$ and $\propto B^{3/2}$, respectively.

Analysis of angular dependence of electrical resistivity

Figure S3(a) shows the same experimental data as those presented in Fig. 4(a) of the main text, and the results of their fitting with the function $\rho(\theta) \propto \cos^2(\theta)$. Clearly, at low temperatures, the experimental data cannot be described well enough, but at higher temperatures the quality of fitting becomes better and above at least $150 \text{K}$ this function suits perfectly. Figure S3(b) shows the adjusted R-square parameter, $R^2_A$, reflecting the quality of the fit [SR3], as a function of temperature at which was measured $\rho(\theta)$ dataset for which the fitting was performed. For a perfect fit $R^2_A$ should be equal to 1. In the present case, $R^2_A$ is very close to 1 only for temperatures higher than $75 \text{K}$.

FIG. S3 (a) Angular dependence of the electrical resistivity of single-crystalline DyPdBi measured as described in the main text at several different temperatures in magnetic field $B = 14 \text{T}$. Red lines represent the fits with the function $\rho(\theta) \propto \cos^2(\theta)$. (b) Adjusted $R$-square obtained from fitting the function $\rho(\theta) \propto \cos^2(\theta)$ to the data presented in panel (a). Solid line is a guide for the eye.
Hall coefficient versus temperature

Figure S4 shows the temperature dependencies of the Hall coefficient of DyPdBi, $R_H$, obtained in two different ways. One approach was to consider initial slopes of linear fits to the experimental $\rho_{xy}(B)$ data measured in weak magnetic fields, while another one was that described in the main text – using $\rho_{xy}$ values measured in $B = 14$ T. In both cases, we obtained similar values of $R_H$, and the main difference is the temperature at which $R_H(T)$ achieves its maximum. For $R_H$ calculated as a slope of $\rho_{xy}(B)$, this temperature is lower than in case of $R_H$ being calculated from the Hall resistivity, $\rho_{xy}$, measured in $B = 14$ T. In consequence, $R_H(T)$ calculated by the former method has a behavior more similar to the temperature dependence of the planar Hall effect amplitude, $\Delta \rho(T)$, than that calculated by the latter method.

**FIG. S4** Temperature dependence of the Hall coefficient of DyPdBi (olive stars) obtained as a slope of linear fits to the $\rho_{xy}(B)$ curves in weak fields, presented in Fig. 5(a) of the main text. For comparison, there is shown the $R_H(T)$ dependence (blue circles) reproduced from the inset to Fig. 5(b) of the main text. Solid lines are guides for the eye.

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