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Ding-Fu Shao  
*University of Nebraska - Lincoln*

Gautam Gurung  
*University of Nebraska - Lincoln*

Shu-Hui Zhang  
*Beijing University of Chemical Technology*

Evgeny Y. Tsymbal  
*University of Nebraska - Lincoln*

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Dirac Nodal Line Metal for Topological Antiferromagnetic Spintronics

Ding-Fu Shao,1,* Gautam Gurung,1 Shu-Hui Zhang,2 and Evgeny Y. Tsymbal1,†

1Department of Physics and Astronomy & Nebraska Center for Materials and Nanoscience, University of Nebraska, Lincoln, Nebraska 68588-0299, USA
2College of Science, Beijing University of Chemical Technology, Beijing 100029, People’s Republic of China

Department of Physics and Astronomy & Nebraska Center for Materials and Nanoscience, University of Nebraska, Lincoln, Nebraska 68588-0299, USA

Topological antiferromagnetic (AFM) spintronics is an emerging field of research, which exploits the Néel vector to control the topological electronic states and the associated spin-dependent transport properties. A recently discovered Néel spin-orbit torque has been proposed to electrically manipulate Dirac band crossings in antiferromagnets; however, a reliable AFM material to realize these properties in practice is missing. In this Letter, we predict that room-temperature AFM metal MnPd$_2$ allows the electrical control of the Dirac nodal line by the Néel spin-orbit torque. Based on first-principles density functional theory calculations, we show that reorientation of the Néel vector leads to switching between the symmetry-protected degenerate state and the gapped state associated with the dispersive Dirac nodal line at the Fermi energy. The calculated spin Hall conductivity strongly depends on the Néel vector orientation and can be used to experimentally detect the predicted effect using a proposed spin-orbit torque device. Our results indicate that AFM Dirac nodal line metal MnPd$_2$ represents a promising material for topological AFM spintronics.

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The discovery of novel quantum phenomena in solids, resulting from the interplay between the electron, spin, and orbital degrees of freedom, enriches a continuously evolving field of spintronics and opens opportunities to enhance the efficiency of electronic devices [1]. Recently, antiferromagnetic (AFM) spintronics has emerged as a subfield of spintronics, where an AFM order parameter also known as the Néel vector is exploited to control spin-dependent transport properties [2–4]. Because they are robust against magnetic perturbations, producing no stray fields and exhibiting ultrafast dynamics, antiferromagnets can serve as promising functional materials for spintronic applications, which may expand to very diverse areas ranging from terahertz information technologies to artificial neural networks [5].

The interest in AFM spintronics has largely been stimulated by the recent discovery of electrical switching of a collinear antiferromagnet by spin-orbit torque [6]. It is known that spin-orbit torques can originate from the inverse spin-galvanic effect [7], which occurs in magnetic materials with broken space-inversion symmetry due to spin-orbit coupling (SOC) [8–11]. If an antiferromagnet is formed of two antiparallel-aligned spin sublattices, whose atomic structure has broken space-inversion symmetry but the sublattices form space-inversion partners, the inverse spin-galvanic effect produces a nonequilibrium local spin polarization of opposite sign on the two spin sublattices. The resulting staggered effective magnetic field generates an alternating-in-sign spin-orbit torque, known as the Néel spin-orbit torque, on the sublattice magnetizations, thus acting with a torque on the Néel vector [12,13]. The control of the Néel vector by electric current has been realized using tetragonal CuMnAs [6] and Mn$_2$Au [14] antiferromagnets, thus demonstrating a viable approach to the AFM-based memories [15] and providing a route to ultrafast spintronic devices [4,5].

In parallel with these developments, there has been increasing interest in materials and structures where quantum effects are responsible for novel physical properties, revealing the important roles of symmetry, topology, and dimensionality [16]. Among such quantum materials are graphene [17], topological insulators [18], Dirac and Weyl semimetals [19], and beyond [20]. These materials are characterized by nontrivial fermionic excitations resulting from discrete band crossings as well as continuous degenerate states, such as the nodal lines [21,22] and their exotic connections [23,24]. Using the unique properties of the novel fermionic states has been envisioned for spintronics applications [25,26]. A particular example is the demonstration of significantly enhanced spin-orbit torques in ferromagnet/topological insulator heterostructures [27,28].

The discovery of the electrical control of the Néel vector [6,14] opens a new direction in spintronics, involving the interplay between the topological electronic states and antiferromagnetism [29,30]. A notable example is the proposed control of Dirac quasiparticles in an antiferromagnet by reorientation of the Néel vector [31]. ON and OFF switching of the symmetry protection of the Dirac band crossing has been predicted in an AFM Dirac semimetal, such as orthorhombic CuMnAs [32], resulting in the...
topological metal-insulator transition [Figs. 1(a) and 1(d)] and topological anisotropic magnetoresistance [31].

To realize these properties in practice, however, the Dirac quasiparticles are required to appear precisely at the Fermi energy ($E_F$), demanding a strict control of the stoichiometry and structural quality of the sample, which is not easy to achieve in real experimental conditions. On the other hand, there exists a class of quantum materials exhibiting Dirac nodal lines within a broad energy window including those crossing the Fermi energy. In an AFM material with such a nodal line, the Néel spin-orbit torque control of the Dirac band crossings would be much easier to realize and detect in transport measurements [Figs. 1(e) and 1(f)].

In this Letter, we predict that the AFM metal MnPd$_2$ has the desired properties: It has the required symmetry to support the Néel spin-orbit torque, and it holds a dispersive Dirac nodal line across the Fermi energy. The reorientation of the Néel vector leads to switching between the symmetry-protected degenerate state and the gapped state associated with the Dirac nodal line. We show that the spin Hall conductivity of MnPd$_2$ strongly depends on the Néel vector orientation and can be used to detect the effect. MnPd$_2$ has been synthesized in the laboratory, has Néel temperature ($T_N$) well above room temperature, and thus represents a new promising material for topological antiferromagnetic spintronics.

FIG. 1. Controlling a Dirac point or a Dirac nodal line by the Néel vector. (a), (b) Schematics of an antiferromagnet with two magnetic sublattices (denoted as Mn$_A$ and Mn$_B$) connected by the PT symmetry for two orientations of the Néel vector, preserving (a) and breaking (b) glide symmetry $g_z$ (indicated by the dotted lines). Red arrows indicate the magnetic moments. (c)–(f) Schematics of the band structure around the Fermi energy ($E_F$) for a Dirac point (c), (d) or a dispersive Dirac nodal line (e), (f) for preserved (c), (e) or broken (d), (f) glide symmetry $g_z$.

FIG. 2. Néel vector controlled Dirac nodal line in MnPd$_2$. (a) Crystal structure of MnPd$_2$. Two magnetic sublattices Mn$_A$ and Mn$_B$ are connected by the PT symmetry. Red arrows indicate the Mn magnetic moments. (b) Schematic of the glide $g_z$ symmetry for $\vec{n} || [001]$, which connects two Mn atoms in the same sublattice via mirror reflection $M_z$, followed by translation $(\frac{1}{2}, 0, 0)$ (indicated by the black dashed lines). (c), (d) Band structure of MnPd$_2$ in the $k_z = (\pi/c)$ plane for $\vec{n} || [001]$ (c) and $\vec{n} || [010]$ (d). The two bands forming the Dirac nodal line are indicated by dark red. Arrows in (c) indicate the symmetry-protected Dirac band crossings. (e), (f) Energy dispersions of the two crossing bands in the $k_z = (\pi/c)$ plane for $\vec{n} || [001]$ (e) and $\vec{n} || [010]$ (f). The Dirac nodal line and its projection to the $k_z = (\pi/c)$ plane are shown by the purple and red lines, respectively.
combined $PT$ symmetry is preserved. This condition is sufficient to produce the Néel spin-orbit torque on the Néel vector by passing an electric current [31]. Our calculation of the total energy predicts the lower energy for the Néel vector ($\hat{n}$) lying in the (100) plane with the magnetocrystalline anisotropy energy of $E_{\text{an}} = 0.14$ meV/f.u.

This result is consistent with the experiment [33], showing that the easy axis lies along the [010] direction ($\hat{n}||[010]$). The calculated magnetic moment of 3.89 $\mu_B$ per Mn atom is also in agreement with that (4.0 $\mu_B$) found by this experiment.

The AFM ordering determines the magnetic space group symmetry of MnPd$_2$, as shown in Table S1 in the Supplemental Material [34]. It is evident that the non-symmetric symmetries can be turned on and off by rotating the Néel vector. As we will see below, this leads to the ability to close and open a gap at the Dirac nodal line and thus to control spin-dependent transport properties of MnPd$_2$.

Our density functional theory calculations [34] predict that around the Fermi energy, the electronic band structure of MnPd$_2$ is represented by the Mn and Pd 5$d$ orbitals (Fig. S1). Because of the preserved $PT$ symmetry, every band is doubly degenerate. As seen from Fig. S2, there are three bands crossing $E_F$. Below, we focus on the bands around $E_F$ lying in the $k_z = (\pi/c)$ plane, which form a Dirac nodal line.

Figures 2(c) and 2(d) show the calculated band structure along the high symmetry paths in the $Z$-$U$ plane surrounding the Z point [Fig. 2(e)]. This Dirac nodal line is dispersive, covering a wide energy window ranging from $E \approx -0.071$ eV to $E \approx 0.192$ eV.

Reorientation of the Néel vector breaks the glide symmetry $g_z = \{M_z \mid \{\frac{1}{2}, 0, \frac{1}{2}\}\} [34]$, leading to a looplike Dirac nodal line in the $k_z = (\pi/c)$ plane at $E = 0.192$ eV along the Z-R line [indicated by arrows in Fig. 2(c)]. These crossings are protected by the glide symmetry preserving the $Z$-point rotational degeneracy: at $E = -0.071$ eV along the Z-U line, at $E = 0.234$ eV along the $Z$-$T$ line, and at $E = 0.192$ eV along the $Z$-$R$ line.

The spin Hall conductivity is given by [41]

$$\sigma_{ij}^z = \frac{e^2}{h} \int \frac{d^3\vec{k}}{(2\pi)^3} \sum_n f_{nk} \Omega_{n,ij}^z(\vec{k}), \quad (1)$$

where $f_{nk}$ is the Fermi-Dirac distribution function for band $n$ and wave vector $\vec{k}$, $\Omega_{n,ij}^z(\vec{k})$ is the spin Berry curvature, $J^z = \frac{1}{2} \{v_i, s_k\}$ is the spin-current operator, $v_i$ and $s_k$ are velocity and spin operators, respectively, and $i, j, k = x, y, z$.

The calculated spin Hall conductivities of MnPd$_2$ for $\hat{n}||[001]$ and $\hat{n}||[010]$ are given in Table I. Overall, we find that the predicted magnitude of the spin Hall conductivity in MnPd$_2$ is comparable to that in Ta [42,43], a widely used spin-current source in spin-orbit torque devices [44], but somewhat smaller than that predicted for Pt [45]. Here, we focus on $\sigma_{z\chi}$, as a representative component of the spin Hall conductivity. The other components are discussed in the Supplemental Material [34].

As follows from Eqs. (1) and (2), the spin Hall conductivity is strongly affected by band anticrossings, where the spin Berry curvature is significantly enhanced when the energy separations between bands $n$ and $n'$ at a given $k$ point are small. It is expected, therefore, that switching between the degenerate and gapped states of the Dirac band can lead to a notable change in the spin Hall conductivity, even if such a switchable Dirac point or a Dirac nodal line is buried behind trivial Fermi surfaces [46,47].

In Figs. 3(a) and 3(b), we compare the calculated spin Berry curvature $\Omega_{z\chi}^z$ in the $k_z = (\pi/c)$ plane at $E = E_F$ for $\hat{n}||[001]$ and $\hat{n}||[010]$. We find that while $\Omega_{z\chi}^z$ is small for $\hat{n}||[001]$ in the whole $k_z = (\pi/c)$ plane [Fig. 3(a)], it exhibits a notable peak for $\hat{n}||[010]$ [Fig. 3(b)]. Such a sharp peak appears at different energies and is associated with the Dirac nodal line. As seen from Fig. 3(c), at the points where the nodal line crosses an equi-energy plane, the spin Berry curvature is strongly enhanced [as is indicated by the color contrast in Fig. 3(c)]. Such a sizable change in the spin Berry curvature affects the spin Hall conductivity of MnPd$_2$ and show that it is strongly affected by the orientation of the Néel vector.

<table>
<thead>
<tr>
<th>$\hat{n}$</th>
<th>$\sigma_{z\chi}$</th>
<th>$\sigma_{z\alpha}$</th>
<th>$\sigma_{z\gamma}$</th>
<th>$\sigma_{z\beta}$</th>
<th>$\sigma_{z\delta}$</th>
<th>$\sigma_{z\Omega}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[001]</td>
<td>155.9</td>
<td>-170.7</td>
<td>-104.4</td>
<td>175.2</td>
<td>120.6</td>
<td>-66.7</td>
</tr>
<tr>
<td>[010]</td>
<td>232.0</td>
<td>-176.0</td>
<td>-134.9</td>
<td>138.5</td>
<td>112.7</td>
<td>-66.0</td>
</tr>
</tbody>
</table>
Rotation of the Néel vector in the (100) plane of MnPd$_2$ changes the spin Hall conductivity $\sigma_{xy}$ in an oscillatory fashion [Figs. 4(a) and 4(b)]. The predicted variation of $\sigma_{xy}$, reaching the maximum value of about 50%, can be used to experimentally detect the effect of the Néel spin-orbit torque on the Néel vector in MnPd$_2$, as discussed below.

We note that using anisotropic magnetoresistance [6] to detect the effect is problematic due to the uniaxial magnetocrystalline anisotropy of MnPd$_2$ causing the $\vec{n}||[010]$ state to have lower energy than the $\vec{n}||[001]$ state. As a result, affecting the Néel vector can only occur under conditions of a large steady charge current ($\sim 10^8$–$10^9$ A/cm$^2$) generating the Néel spin-orbit torque. Switching off the charge current leads to the relaxation of the Néel vector back to the equilibrium $\vec{n}||[010]$ direction. This is different from tetragonal CuMnAs [12], which exhibits bi-axial anisotropy, and thus the Néel vector remains stable after its 90º rotation by the Néel spin-orbit torque and then turns off the charge current.

The spin Hall conductivity under the influence of the Néel vector reorientation can be measured using the spin-orbit torque device shown in Fig. 4(c). Here, a ferromagnetic layer is deposited on top of the MnPd$_2$ (100) surface, forming a MnPd$_2$/ferromagnet bilayer. Charge current $J_c$ along the [010] direction is driven by an external source to reorient the Néel vector from the easy [010] axis towards the [001] direction. At the same time, the charge current $J_c$ generates the spin Hall current $J_s$ flowing in the [100] direction and carrying a spin polarization along the [001] direction. This spin current has conductivity $\sigma_{xy}$, which depends on the orientation of the Néel vector, according to Fig. 4(b). The spin current $J_s$ enters the ferromagnetic layer and exerts spin Hall torque $\tau$ on magnetization $M$ of the ferromagnetic layer. When the charge-current density is small, the spin Hall conductivity is constant, corresponding to $\phi = 0$. When the current density becomes sufficiently large, the Néel spin-orbit torque reorients the Néel vector away from its equilibrium [010] direction and the spin Hall conductivity $\sigma_{xy}$ decreases. Since the sizable change of $\sigma_{xy}$ can be obtained even with a small tilting of the Néel vector [Fig. 4(b)], a moderate charge current is sufficient to confirm our prediction. This variation in the spin Hall conductivity can be detected by various standard techniques such as the spin-torque ferromagnetic resonance (ST-FMR) [48], the magneto-optical Kerr effect (MOKE) [49], and the second-harmonic Hall effect [50].

In a similar way, the Néel vector control of the other components of the spin Hall conductivity listed in Table I can be measured by using the appropriate design of the spin-orbit torque device. The proposed approach represents a new way to electrically control the spin Hall conductivity in situ. It is different from the recent approaches to tune the spin Hall effect by changing the scattering center density [51,52], varying the chemical composition [53], or ionic gating [54].
The predicted strong dependence of the spin Hall conductivity on the Néel vector is expected to have non-trivial implications for the dynamics of topological textures, such as domain walls or skyrmions. This dependence can also be reflected in the dynamics of AFM domain walls under moderate spin-orbit torques. Reversible switching of the Néel vector may be realized using ferroelastic strain from a piezoelectric substrate. Overall, we have demonstrated that MnPd$_2$ is a promising material candidate for topological antiferromagnetic spintronics. On one hand, this material has the required magnetic group symmetry to support the Néel spin-orbit torque, which allows the reorientation of the Néel vector. On the other hand, MnPd$_2$ holds a dispersive Dirac nodal line across the Fermi energy. Gap opening and closing along the Dirac nodal line is controlled by the orientation of the Néel vector, which changes the spin Hall conductivity. The latter can be detected by standard techniques using the proposed spin-orbit torque device. We hope that our theoretical predictions will motivate experimentalists to explore the unique properties of MnPd$_2$.

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[34] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.122.077203 for calculation methods, the other details of the electronic structure and spin-Hall conductivity of MnPd₂, the symmetry analysis of the Dirac nodal line, and the influence of strain on the Dirac nodal line, which includes Refs. [35–40].

