Evidence for the Chiral Anomaly in a Dirac Semimetal


Introduction

A long-standing prediction is that the chiral anomaly can appear in 3D crystals that have protected Dirac nodes. All massless Dirac fermions exhibit chiral symmetry. However, coupling to electromagnetic fields breaks the symmetry (a phenomenon called the chiral anomaly). As a result, an axial current flows parallel to the magnetic field $B$. The zero-gap semimetal Na$_3$Bi has two protected Dirac nodes which act as Weyl nodes in $B$. We report the observation of the chiral anomaly as an anomalous, large, negative longitudinal magnetoresistance (LMR). The locking of the axial current plume to $B$ is demonstrated.

Experimental Results

In Na$_3$Bi samples with Fermi energy $E_F$ only 30 mV above the Dirac node (Fig. 1A), the longitudinal resistivity $\rho_{xx}$ decreases 5 fold (Fig. 1B) when a 5-Tesla field $B$ is applied parallel to $E$ (electric field) [1]. The unusual LMR was explored in detail in fields up to 35 T. By rotating both $B$ and $E$ (Fig. 1C), we find that the enhanced current (“axial current plume”) is sharply peaked when $B$ and $E$ are parallel. The angular half-width of the plume decreases with $B$ (to 3° at 9 T). Going to higher $B$, we detect an anomaly at 20 – 28 T (depending on tilt angle $\theta$ of $B$) that implies the opening of an energy gap.

Discussion and conclusions

The two bands derived from Na-3s and Bi-6p orbitals display two intersections which produce protected Dirac nodes along $k_z$. Each Dirac node is a superposition of two Weyl nodes of chiralities $\chi = \pm 1$ (Fig. 1A). In finite $B$, each pair of Weyl nodes acts as a dipole source of Berry curvature. In 1983, Nielsen and Ninomiya predicted that, in applied $B||E$, an axial current $J^5$ should flow. By performing a number of tests (involving independent rotations of the $B$ and $E$ vectors), we have shown that the MR results in Na$_3$Bi confirm this prediction. We also show that the negative LMR is incompatible with Anderson localization (it is highly directional and extends to above 100 K).

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References


Figure 1 (Panel A) Sketch of one Dirac node in Na$_3$Bi as a superposition of Weyl nodes (yellow and grey). Panel B plots the longitudinal $\rho_{xx}$ vs. $B$ at selected temperatures, showing the large negative LMR below 100 K. Panel C displays a series of MR curves at 4.5 K with $B$ tilted to $E$ at selected angles $\phi'$. The negative MR is observed only when $B$ is nearly aligned to $E$ ($\pm 3°$ at 9 T). Adapted from Xiong et al. [1].