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# Large Thermal Hall Effect Detected in Elemental Covalent Insulators

1. **The phonon thermal Hall angle in black Phosphorus**
   Authors: Xiaokang Li, YoMachida,AlaskaSubedi, Zengwei Zhu, LiangLi, Kamran Behnia
   Nature Communications 14, 1027, ( 2023)

2. **Discovery of universal phonon thermal Hall effect in crystals**
   Authors: Xiaobo Jin, Xu Zhang, Wenbo Wan, Hanru Wang, Yihan Jiao and Shiyan Li
   arXiv:2404.02863

3. **Angle-dependent planar thermal Hall effect by quasi-ballistic phonons in black Phosphorus**
   Authors: Xiaokang Li, Xiaodong Guo, Zengwei Zhu, and Kamran Behnia
   arXiv:2406.18816

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The thermal Hall effect (THE), analogous to the charge Hall effect in thermal transport, occurs when a thermal current driven by a longitudinal temperature gradient $\nabla T$ acquires a transverse component under external magnetic field. For insulators, charge-neutral particles are the primary carriers of thermal current, including phonons, magnons, exciton-polaritons, and spinons (in spin-liquid materials). In this case, the thermal Hall effect can be entirely decoupled from the charge Hall effect. Different carriers interact with the magnetic field in distinct ways, which influences the THE. It has long been thought that significant THE are primarily associated with magnetic materials, where magnons can directly couple to the field, and phonons couple through lattice-spin interactions. For nonmagnetic materials, generating a large THE solely via phonons was believed to require specific conditions, such as chiral phonons with finite angular momentum or at least polar phonon modes that can effectively couple to the magnetic field.

The first paper explores the THE in black phosphorus (BP), a typical non-magnetic elemental covalent insulator. BP is a layered material with a puckered honeycomb structure in each layer and belongs to the Cmce (No. 64) space group. The study uncovers a significant thermal Hall conductivity in BP, exceeding that observed in other insulators.

It demonstrates that both transverse and longitudinal thermal conductivities peak at the same temperature, with the thermal Hall angle reaching values between $10^{-4}$ and $10^{-3}$ per Tesla. Unlike conventional cases where the phonon mean-free-path is linked to the thermal Hall angle, this study finds no such correlation, challenging several established theoretical models. The authors attribute the large THE to an anisotropic charge distribution in BP, which may enable phonons to couple with a magnetic field.

The second paper presents the discovery of a universal phonon-mediated topological Hall effect (THE) across a wide range of non-magnetic insulators and semiconductors, including $SrTiO_3$, $SiO_2$ (quartz), $MgO$, $MgAl_2O_4$, $Si$, and $Ge$. Notably, a substantial THE was observed in two elemental insulators, $Si$ and $Ge$. Based on these findings, the authors propose that phonon-induced THE is a significant intrinsic property of crystals. Another key discovery in this paper is the identification of a universal scaling law between longitudinal and transverse thermal transport, expressed as $|\kappa_{xy}| \sim \kappa_{xx}^2$ for intrinsic phonon THE. The authors also noted that external factors, such as magnetic impurities, may influence the specific behavior of phonon THE. The above observations challenge previous interpretations of THE, which often attributed it to magnons or exotic spin excitations in magnetic materials. Instead, the results suggest that THE in crystals arises from a direct interaction between atomic vibrations (phonons) and the magnetic field.

The third paper extends the study of black phosphorus (BP) to the planar THE, where the heat current, temperature gradient, and magnetic field are all confined to the same plane. The results reveal a significant planar thermal Hall signal in BP, peaking when the magnetic field is aligned along one of the two diagonal orientations of its puckered honeycomb lattice, indicating that the response may arise from two distinct contributions along high-symmetry axes. The study also suggests that the torque exerted by the magnetic field on electric dipoles, brought by heat-carrying phonons, could be the underlying mechanism driving the observed effect. Furthermore, in the supplementary materials, the authors compared the thermal Hall coefficients of various materials across different types of insulators studied in recent years, including magnetic insulators, ionic insulators, and elemental covalent insulators. Surprisingly, the elemental covalent insulators BP, Si, and Ge exhibit the largest THE, strongly challenging the conventional understanding of THE. The figure is included below with the permission of the authors.

The above observations suggest that both THE and planar THE are universally present in all band insulators. In non-magnetic insulators, acoustic phonons are the primary contributors. However, no existing theory has successfully explained the large THE observed in elemental covalent insulators. In ionic crystals, the motion of cations and anions directly couples to the magnetic field via the Lorentz force. In reference[1], B. Flebus and A. H. MacDonald proposed a mechanism where the coupling between acoustic phonons and the magnetic field is mediated by an optical phonon mode. In contrast, in elemental covalent insulators, the lattice motion does not experience the Lorentz force directly, as there are no cations or anions and all atoms are equivalent. Although the precise microscopic mechanism through which acoustic phonons in elemental covalent insulators can effectively couple to the magnetic field remains unclear, pioneering theoretical works[2, 3, 4, 5] suggest that the connection between acoustic phonons and the vector potential may be established via the Berry connection, induced by generic electron-phonon coupling in solids. To quantitatively understand the large THE in elemental covalent insulators—particularly its temperature de-

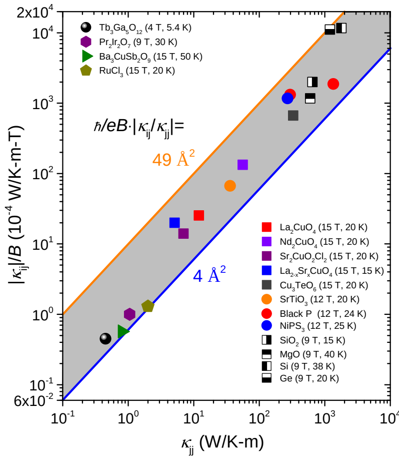


Figure 1: Thermal Hall coefficient (The transverse thermal conductivity divided by magnetic field) in different insulators as a function of longitudinal thermal conductivity in different insulators.

pendence and scaling behavior with longitudinal thermal conductivity further experimental and theoretical studies are required.

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