南方科技大学

优秀博士学位论文申请材料

作者姓名：李帅

导师姓名：卢海舟

学科/专业学位类别：物理学/理学博士

所在院系：物理系

攻读博/硕士学位期间代表性成果

SCI 检索源期刊：

[1] Li Shuai, Liu Tian-Yu, Liu Chang, Wang Ya-Yu, Lu Hai-Zhou, and Xie Xin-Cheng. Progress on Antiferromagnetic Topological Insulator MnBi2Te4 [J]. National Science Review, 2023, DOI: https://doi.org/10.1093/nsr/nwac296 （SCI 收录，IF =23.178，对应学位论文第 5 章）

[2] Li Shuai, Wang Chun-Ming, Du Zong-Zheng, Qin Fang, Lu Hai-Zhou, and Xie Xin-Cheng. 3D Quantum Hall Effects and Nonlinear Hall Effect [J]. npj Quantum Materials, 2021, 6(1): 1-5.（SCI 收录，IF =6.85，对应学位论文第 4 章）

导师对学生参评优秀博士学位论文代表性成果的审查意见：

该生攻读博士期间的代表性成果，数据准确无误、真实可靠，无学术不端和学术失范行为。

导师签字： 卢海舟

日期：2023 年 5 月 4 日

Article Contents

Abstract

JOURNAL ARTICLE ACCEPTED MANUSCRIPT

Progress on antiferromagnetic topological insulator $MnBi_2Te_4$

Shuai Li, Tianyu Liu, Chang Liu, Yayu Wang, Hai-Zhou Lu ✉, X C Xie

National Science Review, nwac296, https://doi.org/10.1093/nsr/nwac296
Published: 03 January 2023

PDF | Split View | Annotate | Cite | Permissions | Share

Abstract

Topological materials, which feature robust surface and/or edge states, have now been a research focus in condensed matter physics. They represent a new class of materials exhibiting nontrivial topological phases, and provide a platform for exploring exotic transport phenomena, such as the quantum anomalous Hall effect and the quantum spin Hall effect. Recently, magnetic topological materials have attracted considerable interests due to the possibility to study the interplay between topological and magnetic orders. In particular, the quantum anomalous Hall and axion insulator phases can be realized in topological insulators with magnetic order. $MnBi_2Te_4$, as the first intrinsic antiferromagnetic topological insulator discovered, allows the examination of existing theoretical predictions; it has been extensively studied, and many new discoveries have been made. Here we review the progress made in $MnBi_2Te_4$ from both experimental and theoretical aspects. The bulk crystal and magnetic structures are surveyed first, followed by a review of theoretical calculations and experimental probes on the band structure and surface states, and a discussion of various exotic phases that can be realized in $MnBi_2Te_4$. The properties of $MnBi_2Te_4$ thin films and the corresponding transport studies are then reviewed, with an emphasis on the edge state transport. Possible future research directions in this field are also discussed.

Keywords: $MnBi_2Te_4$, magnetic topological insulator, antiferromagnetic, quantum anomalous Hall effect, axion insulator

Subject: Physics

Issue Section: Review

REVIEW

[1]Department of Physics, Harbin Institute of Technology, Harbin 150001, China; [2]Shenzhen Institute for Quantum Science and Engineering and Department of Physics, Southern University of Science and Technology (SUSTech), Shenzhen 518055, China; [3]Shenzhen Key Laboratory of Quantum Science and Engineering, Shenzhen 518055, China; [4]International Quantum Academy, Shenzhen 518048, China; [5]State Key Laboratory of Low Dimensional Quantum Physics, Department of Physics, Tsinghua University, Beijing 100084, China; [6]Beijing Key Laboratory of Optoelectronic Functional Materials & Micro-Nano Devices, Department of Physics, Renmin University of China, Beijing 100872, China; [7]Frontier Science Center for Quantum Information, Beijing 100084, China; [8]International Center for Quantum Materials, School of Physics, Peking University, Beijing 100871, China; [9]Collaborative Innovation Center of Quantum Matter, Beijing 100871, China; [10]CAS Center for Excellence in Topological Quantum Computation, University of Chinese Academy of Sciences, Beijing 100190, China

*Corresponding authors. E-mail: luhz@sustech.edu.cn.

Received: XX XX Year; **Revised:** XX XX Year; **Accepted:** XX XX Year

PHYSICS

Progress on antiferromagnetic topological insulator $MnBi_2Te_4$

Shuai Li[1,2,3,4], Tianyu Liu[2,3,4], Chang Liu[5,6,9], Yayu Wang[5,7], Hai-Zhou Lu[2,3,4,*] and X. C. Xie[8,9,10]

ABSTRACT

Topological materials, which feature robust surface and/or edge states, have now been a research focus in condensed matter physics. They represent a new class of materials exhibiting nontrivial topological phases, and provide a platform for exploring exotic transport phenomena, such as the quantum anomalous Hall effect and the quantum spin Hall effect. Recently, magnetic topological materials have attracted considerable interests due to the possibility to study the interplay between topological and magnetic orders. In particular, the quantum anomalous Hall and axion insulator phases can be realized in topological insulators with magnetic order. $MnBi_2Te_4$, as the first intrinsic antiferromagnetic topological insulator discovered, allows the examination of existing theoretical predictions; it has been extensively studied, and many new discoveries have been made. Here we review the progress made in $MnBi_2Te_4$ from both experimental and theoretical aspects. The bulk crystal and magnetic structures are surveyed first, followed by a review of theoretical calculations and experimental probes on the band structure and surface states, and a discussion of various exotic phases that can be realized in $MnBi_2Te_4$. The properties of $MnBi_2Te_4$ thin films and the corresponding transport studies are then reviewed, with an emphasis on the edge state transport. Possible future research directions in this field are also discussed.

Keywords: $MnBi_2Te_4$, magnetic topological insulator, antiferromagnetic, quantum anomalous Hall effect, axion insulator

INTRODUCTION

The discovery of the quantum Hall effect (QHE) opens a new chapter in condensed matter physics [1]. The quantized conductance is a manifestation of the quantum effect on the macroscopic scale; it is precisely determined in terms of fundamental constants: the electron charge e and the Planck constant h. Studies on QHE have led to a revolution in the classification of different topological phases of matter [2,3]. The concept of topological insulators (TIs) was proposed, and the corresponding materials were then found in experiments [2,3]. Subsequently, topological semimetals were theoretically predicted and experimentally realized [4,5]. In turn, these topological materials provide an ideal platform for exploring exotic transport phenomena. The quantum spin Hall effect (QSHE) and the quantum anomalous Hall effect (QAHE) were realized [6–9], both of which are supported by the distinguished edge states of topological materials in the absence of magnetic fields. Other generalizations of QHE such as the 3D QHE and the nonlinear Hall effect have also been explored [10]. In recent years, magnetic TIs have attracted great interests because they can host QAHE and offer opportunities to investigate the intertwined topological and magnetic orders [11]. $MnBi_2Te_4$, as the first intrinsic antiferromagnetic (AFM) topological insulator discovered, has been extensively studied.

$MnBi_2Te_4$ was first discovered and synthesized in 2013, with its thermoelectric properties investigated [12]. Riding on a wave of research on topological insulators, researchers started to pay attention to $MnBi_2Te_4$ because of its magnetism contributed by the Mn atoms. In 2017, the ($MnBi_2Te_4$ layer)-(TI film)-($MnBi_2Te_4$ layer) heterostructure was proposed as a platform for QAHE [13]. Through first-principles calculations, the authors found a large

Perspective | Open Access | Published: 25 November 2021

3D quantum Hall effects and nonlinear Hall effect

Shuai Li, C. M. Wang, Z. Z. Du, Fang Qin, Hai-Zhou Lu & X. C. Xie

npj Quantum Materials 6, Article number: 96 (2021) | Cite this article

Abstract

The classical and quantum Hall effects are important subjects in condensed matter physics. The emergent 3D quantum Hall effects and nonlinear Hall effect have attracted considerable interest recently, with the former elevating the quantum Hall effect to a higher dimension and the latter extending the Hall effect to higher-order responses. In this perspective, we briefly introduce these two new members of the Hall family and discuss the open questions and future research directions.

Introduction

The Hall effects have long been research focus in condensed matter physics[1,2,3]. In particular, the quantum Hall effect[4,5], which manifests as the quantized Hall resistance and zero longitudinal resistance of the two-dimensional electron gas in a strong magnetic field, is one of the greatest discoveries in physics. Thus far, there have been four main generalizations of the quantum Hall effect: fractionalization, no magnetic field, higher dimension, and nonlinearity. The first generalization, the fractional quantum Hall effect, was the subject of the 1998 Nobel Prize in Physics[6,7]. The study of the quantum Hall effect in the absence of a magnetic field has led to the discoveries of several topological states of matter[8,9,10,11,12,13,14,15,16,17]. Recently, rapid progress has been made on the latter two generalizations, that is, the 3D quantum Hall effects and the nonlinear Hall effect. In this perspective, we introduce these two new members of the Hall family, focusing on both experimental and theoretical aspects, and discuss the open questions and future directions.

3D quantum Hall effects

Researchers have been attempting to realize the quantum Hall effect in 3D systems over 30 years[18,19,20,21,22,23,24,25,26,27,28,29,30,31]. Recently, the quantizations of Hall conductance and Hall conductivity have been observed in 3D devices of Cd_3As_2[32,33,34,35,36,37] and $ZrTe_5$[38], respectively. The former is based on topologically protected Fermi arcs in topological semimetals, and the latter is believed to arise from the charge-density wave (CDW) of the Landau bands.

Rights and permissions

About this article

Check for updates

Cite this article

Li, S., Wang, C.M., Du, Z.Z. *et al.* 3D quantum Hall effects and nonlinear Hall effect. *npj Quantum Mater.* **6**, 96 (2021). https://doi.org/10.1038/s41535-021-00399-2

Download citation

Received	Accepted	Published
26 May 2021	21 October 2021	25 November 2021

DOI
https://doi.org/10.1038/s41535-021-00399-2

Share this article

Anyone you share the following link with will be able to read this content:

Get shareable link

Provided by the Springer Nature SharedIt content-sharing initiative

Subjects

Condensed-matter physics Quantum physics

This article is cited by

Strong room-temperature bulk nonlinear Hall effect in a spin-valley locked Dirac material
Lujin Min, Hengxin Tan ... Zhiqiang Mao
Nature Communications (2023)

npj | Quantum Materials

www.nature.com/npjquantmats

PERSPECTIVE OPEN

Check for updates

3D quantum Hall effects and nonlinear Hall effect

Shuai Li[1,2,3], C. M. Wang[2,3,4], Z. Z. Du[2,3], Fang Qin[2,3], Hai-Zhou Lu[2,3]✉ and X. C. Xie[5,6,7]

The classical and quantum Hall effects are important subjects in condensed matter physics. The emergent 3D quantum Hall effects and nonlinear Hall effect have attracted considerable interest recently, with the former elevating the quantum Hall effect to a higher dimension and the latter extending the Hall effect to higher-order responses. In this perspective, we briefly introduce these two new members of the Hall family and discuss the open questions and future research directions.

npj Quantum Materials (2021)6:96 ; https://doi.org/10.1038/s41535-021-00399-2

INTRODUCTION

The Hall effects have long been research focus in condensed matter physics[1–3]. In particular, the quantum Hall effect[4,5], which manifests as the quantized Hall resistance and zero longitudinal resistance of the two-dimensional electron gas in a strong magnetic field, is one of the greatest discoveries in physics. Thus far, there have been four main generalizations of the quantum Hall effect: fractionalization, no magnetic field, higher dimension, and nonlinearity. The first generalization, the fractional quantum Hall effect, was the subject of the 1998 Nobel Prize in Physics[6,7]. The study of the quantum Hall effect in the absence of a magnetic field has led to the discoveries of several topological states of matter[8–17]. Recently, rapid progress has been made on the latter two generalizations, that is, the 3D quantum Hall effects and the nonlinear Hall effect. In this perspective, we introduce these two new members of the Hall family, focusing on both experimental and theoretical aspects, and discuss the open questions and future directions.

3D QUANTUM HALL EFFECTS

Researchers have been attempting to realize the quantum Hall effect in 3D systems over 30 years[18–31]. Recently, the quantizations of Hall conductance and Hall conductivity have been observed in 3D devices of Cd_3As_2[32–37] and $ZrTe_5$[38], respectively. The former is based on topologically protected Fermi arcs in topological semimetals, and the latter is believed to arise from the charge-density wave (CDW) of the Landau bands.

In topological semimetals, the conduction and valence bands touch at the Weyl points. The Fermi arcs are the Fermi surface of the topologically protected surface states of the topological semimetals (Fig. 1a). At a single surface, the Fermi-arc surface states cannot form a complete 2D electron gas to support the cyclotron motion of electrons, which rules out the Landau levels and quantum Hall effect. It has been proposed that the 2D Fermi-arc surface states from different surfaces can be connected at the Weyl points[39–41] to form a complete 2D electron gas to support the 3D quantum Hall effect[32,33] (Fig. 1b). In real space, driven by a perpendicular magnetic field, an electron performs half of a cyclotron motion on the top surface and then tunnels to the bottom surface to complete the cyclotron motion. This Fermi-arc mechanism of the 3D quantum Hall effect is characterized by the one-sided edge states, which reside at one side on the top surface but the opposite side on the bottom. The quantized Hall conductance has been observed in the topological Dirac semimetal Cd_3As_2[34–37]. However, the Dirac semimetal consists of two time-reversed Weyl semimetals; thus, on a single surface, the time-reversed Fermi-arc surface states could also support a conventional 2D quantum Hall effect. To identify the top-bottom Fermi-arc 3D quantum Hall effect, a wedge-shaped Hall bar has been used, in which an extra in-plane magnetic field can induce a geometric phase that depends on the sample thickness[37]. As the measurement position of the Hall voltage electrodes is changed, the effective thickness is changed, and a systematic shift of the quantum Hall conductance plateaus occurs (Fig. 1c), strongly supporting the Fermi-arc origin of this 3D quantum Hall effect.

The quantum Hall effect observed in $ZrTe_5$[38] has a different mechanism, owing to the formation of CDW. For 3D materials under magnetic fields, the Fermi energy usually crosses the Landau bands. Thus, the bulk states contribute unquantized Hall conductance. However, forming of CDW states can open a band gap at the Fermi energy (Fig. 1e). In real space, the electrons, that form the CDW states along the magnetic field direction, are distributed periodically with the period λ (half of the Fermi wavelength). This makes the material look like a stack of 2D electron layers. Therefore, the quantized Hall resistivity is,

$$\rho_{xy} = \frac{h}{e^2}\lambda \tag{1}$$

In the experiment[38], there are several evidences to support the CDW mechanism of the 3D quantum Hall effect. First, the 3D ellipsoidal Fermi surface of the samples is confirmed by the Shubnikov-de Haas oscillation measurements. This excludes the possibility that the system is originally composed of 2D electron layers. Second, the Hall resistivity shows plateaus when the magnetic field strength is approximately 2 T, at which time the longitudinal resistivity also drops to zero (Fig. 1d). The value of quantized Hall resistivity is consistent with Eq. (1), and λ is found to be approximately half of the Fermi wavelength along the magnetic field direction for all four samples, i.e., $\lambda = \pi/k_{F,z}$, consistent with the feature of the CDW wavelength. Third, the existence of the CDW is supported by the non-Ohmic I-V characteristic (Fig. 1f). The non-Ohmic I-V characteristic is another

[1]Department of Physics, Harbin Institute of Technology, Harbin 150001, China. [2]Shenzhen Institute for Quantum Science and Engineering and Department of Physics, Southern University of Science and Technology (SUSTech), Shenzhen 518055, China. [3]Shenzhen Key Laboratory of Quantum Science and Engineering, Shenzhen 518055, China. [4]Department of Physics, Shanghai Normal University, Shanghai 200234, China. [5]International Center for Quantum Materials, School of Physics, Peking University, Beijing 100871, China. [6]Beijing Academy of Quantum Information Sciences, Beijing 100193, China. [7]CAS Center for Excellence in Topological Quantum Computation, University of Chinese Academy of Sciences, Beijing 100190, China. ✉email: luhz@sustech.edu.cn