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东图·学术快报

物理学 Nature & Science 发文 (1月)

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前言

/Foreword

前沿经典

学科热点

学术动态

工具助手

美国 Science (《科学》)、英国 Nature (《自然》) 及美国 Cell (《细胞》) 是国际公认的三大享有最高学术声誉的科技期刊，发表在这三大期刊上的论文简称 CNS 论文。

本期梳理 2025 年 1 月 Nature、Science 期刊上物理学领域的最新论文。

(2025. 1)



[1] Photonic axion insulator

光子轴子绝缘体

出版信息: Science, VOLUME 387, ISSUE 6730, 10 JAN 2025

作者: GUI-GENG LIU, SUBHASKAR MANDAL, XIANG XI, QIANG WANG, CHIARA DEVESCOVI, ANTONIO MORALES-PÉREZ, ET AL.

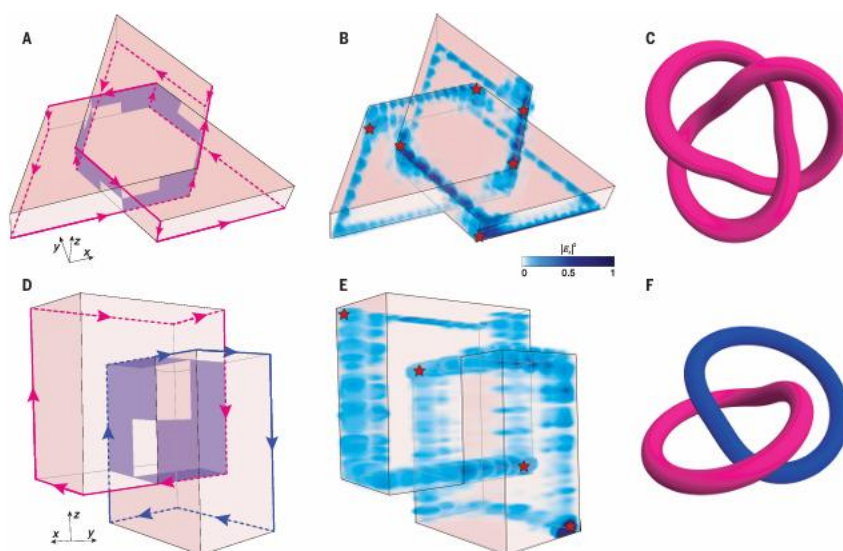
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全文链接: <https://www.science.org/doi/10.1126/science.adr5234>

Abstract: Axions, hypothetical elementary particles that remain undetectable in nature, can arise as quasiparticles in three-dimensional crystals known as axion insulators. Previous implementations of axion insulators have largely been limited to two-dimensional systems, leaving their topological properties in three dimensions unexplored in experiment. Here, we realize an axion insulator in a three-dimensional photonic crystal and probe its topological properties. Demonstrated features include half-quantized Chern numbers on each surface that resembles a fractional Chern insulator, unidirectional chiral hinge states forming topological transport in three dimensions, and arithmetic operations between fractional and integer Chern numbers. Our work experimentally establishes the axion insulator as a three-dimensional topological phase of matter and enables chiral states to form complex, unidirectional three-dimensional networks through braiding.

摘要翻译: 轴子是一种假设的基本粒子，在自然界中无法探测到，其可以作为准粒子出现在被称为轴子绝缘体的三维晶体中。先前轴子绝缘体的实现在很大程度上局限于二维系统，在实验中尚未探索其三维拓扑特性。研究组在三维光子晶体中实现了一种轴子绝缘子，并研究了其拓扑性质。实验演示的特征包括每个表面上类似于分数陈氏绝缘子的半量子化陈数，在三维中形成拓扑运输的单向手性铰链态，以及分数陈数和整数陈数之间的算术运算。该工作通过实验将轴子绝缘体确立为物质的三维拓扑相，并实现了手性态通过编织形成复杂的单向三维网络。

文中插图:



[2] Quadruple-band synglisis enables high thermoelectric efficiency in earth-abundant tin sulfide crystals

四能带合成使地球储量丰富的硫化锡晶体具有高热电效率

出版信息: Science, VOLUME 387, ISSUE 6730, 10 JAN 2025

作者: SHAN LIU, SHULIN BAI, YI WEN, JING LOU, YONGZHEN JIANG, YINGCAI ZHU, ET AL.

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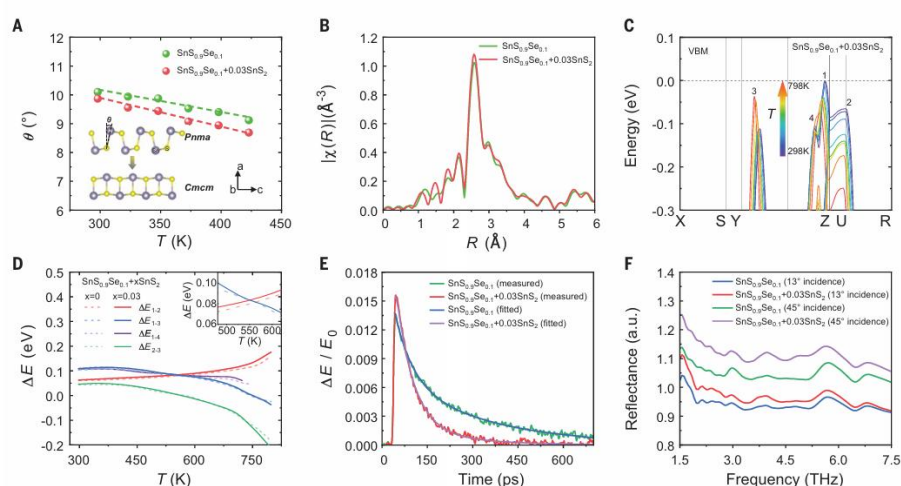
全文链接: <https://www.science.org/doi/10.1126/science.ado1133>

国内报道: <https://h3i.buaa.edu.cn/info/1189/2830.htm>

Abstract: Thermoelectrics have been limited by the scarcity of their constituent elements, especially telluride. The earth-abundant, wide-bandgap ($E_g \approx 46$ kBT) tin sulfide (SnS) has shown promising performance in its crystal form. We improved the thermoelectric efficiency in SnS crystals by promoting the convergence of energy and momentum of four valence bands, termed quadruple-band synglisis. We introduced more Sn vacancies to activate quadruple-band synglisis and facilitate carrier transport by inducing SnS₂ in selenium (Se)-alloyed SnS, leading to a high dimensionless figure of merit (ZT) of ~ 1.0 at 300 kelvin and an average ZT of ~ 1.3 at 300 to 773 kelvin in p-type SnS crystals. We further obtained an experimental efficiency of $\sim 6.5\%$, and our fabricated cooler demonstrated a maximum cooling temperature difference of ~ 48.4 kelvin at 353 kelvin. Our observations should draw interest to earth-abundant SnS crystals for applications of waste-heat recovery and thermoelectric cooling.

摘要翻译: 热电材料一直受到其组成元素稀缺的限制,尤其是碲化物。地球上储量丰富的宽禁带 ($E_g \approx 46$ kBT) 硫化锡 (SnS) 在晶体形态上表现出颇具前景的性能。研究组通过促进四个价带的能量和动量辐合来提高 SnS 晶体的热电效率,称为四能带合成。他们在硒 (Se) 合金 SnS 中引入了更多的 Sn 空位来激活四能带合成,并通过诱导 SnS₂ 来促进载流子的传输,从而实现 p 型 SnS 晶体在 300 K 温度下约 1.0 的高无量纲品质系数 (ZT),在 300 K ~ 773 K 温度下的平均 ZT 为 1.3。研究组进一步获得了 6.5% 的实验效率,其制造的冷却器在 353 K 时的最大冷却温差为 48.4 K。该发现有望引起人们对地球上储量丰富的 SnS 晶体在废热回收和热电冷却方面应用的兴趣。

文中插图:



物理学 Nature 论文

[1] Particle exchange statistics beyond fermions and bosons

超越费米子和玻色子的粒子交换统计

出版信息: Nature, Volume 637 Issue 8045, 9 January 2025

作者: Zhiyuan Wang & Kaden R. A. Hazzard

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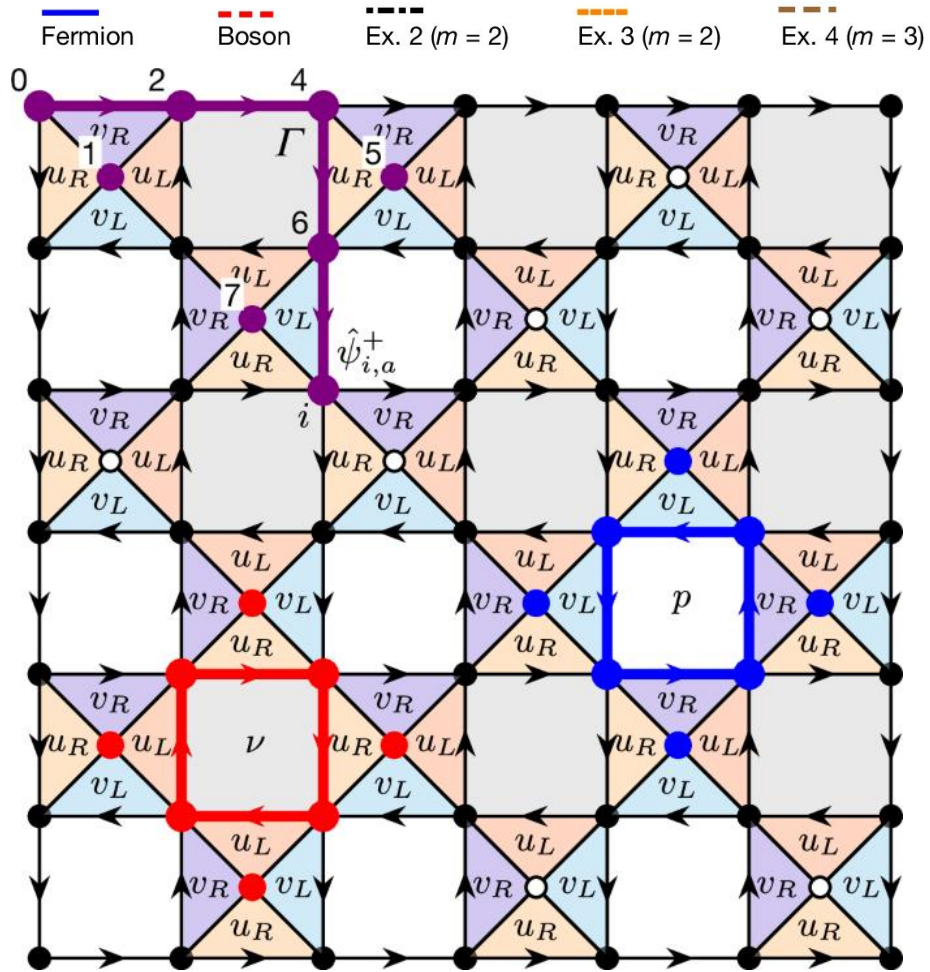
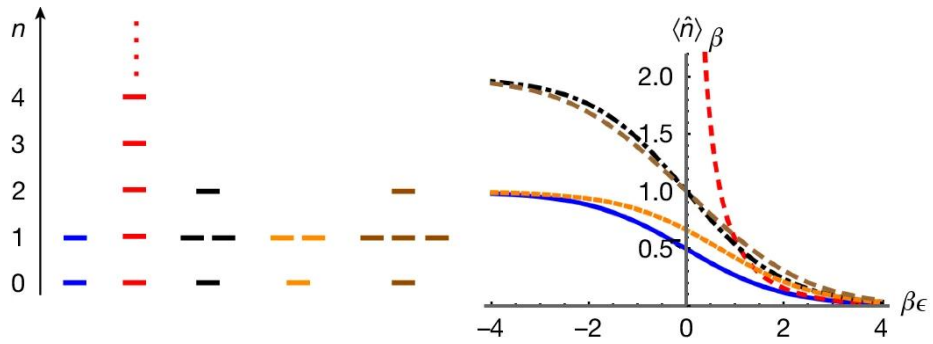
全文链接: <https://www.nature.com/articles/s41586-024-08262-7>

Abstract: It is commonly believed that there are only two types of particle exchange statistics in quantum mechanics, fermions and bosons, with the exception of anyons in two dimensions. In principle, a second exception known as parastatistics, which extends outside two dimensions, has been considered but was believed to be physically equivalent to fermions and bosons. Here we show that non-trivial parastatistics inequivalent to either fermions or bosons can exist in physical systems. These new types of identical particle obey generalized exclusion principles, leading to exotic free-particle thermodynamics distinct from any system of free fermions and bosons. We formulate our theory by developing a second quantization of paraparticles that naturally includes exactly solvable non-interacting theories and incorporates physical constraints such as locality. We then construct a family of exactly solvable quantum spin models in one and two dimensions, in which free paraparticles emerge as quasiparticle excitations, and their exchange statistics can be physically observed and are notably distinct from fermions and bosons. This demonstrates the possibility of a new type of quasiparticle in condensed matter systems and—more speculatively—the potential for previously unconsidered types of elementary particle.

摘要翻译: 人们普遍认为, 在量子力学中, 除了二维的任意子, 只有费米子和玻色子两种粒子交换统计。原则上, 第二种例外被称为非统计。它延伸到二维之外, 被认为在物理上等同于费米子和玻色子。研究者证明了物理系统中可以存在与费米子或玻色子等价的非平凡准统计量。这些新类型的相同粒子遵循广义不相容原理, 导致与任何自由费米子和玻色子系统不同的奇异自由粒子热力学。他们通过发展粒子的第二次量子化来表述其理论。该理论自然地包括精确可解的非相互作用理论, 并结合了诸如局部性等物理约束。然后, 他们在一维和二维中构建了一组精确可解的量子自旋模型, 其中自由粒子以准粒子的形式出现, 其交换统计量可以被物理观察到, 且与费米子和玻色子明显不同。这证明了在凝聚态系统中存在一种新型准粒子的可能性, 更有可能是以前未考虑过的基本粒子类型。

文中插图:





[2] Excitons in the fractional quantum Hall effect

分数量子霍尔效应中的激子

出版信息: Nature, Volume 637 Issue 8045, 9 January 2025

作者: Naiyuan J. Zhang, Ron Q. Nguyen, Navketan Batra, Xiaoxue Liu, Kenji Watanabe, Takashi Taniguchi, D. E. Feldman & J. I. A. Li

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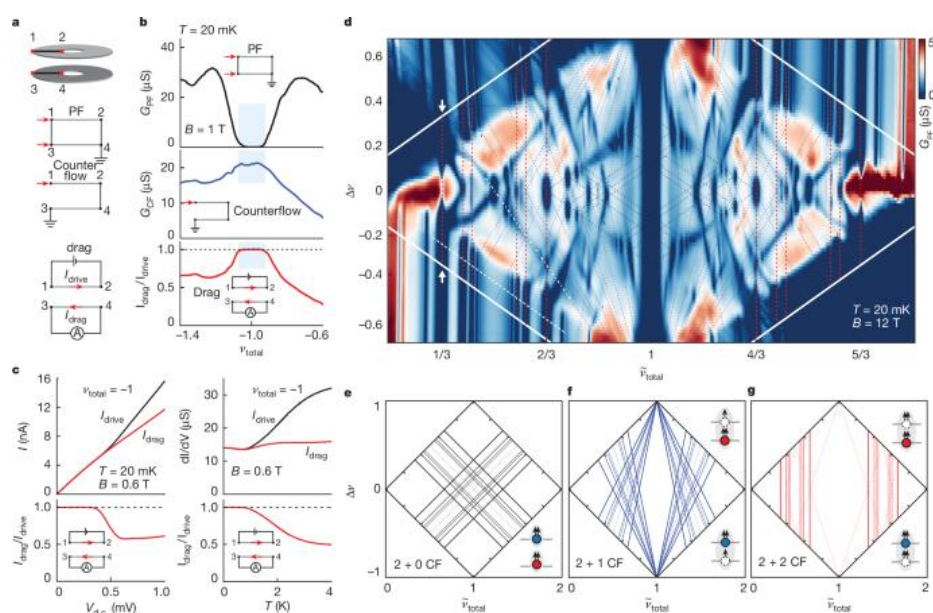
Brown Theoretical Physics Center, Brown University, Providence, RI, USA

全文链接: <https://www.nature.com/articles/s41586-024-08274-3>

Abstract: Excitons, Coulomb-driven bound states of electrons and holes, are typically composed of integer charges. However, in bilayer systems influenced by charge fractionalization, a more interesting form of interlayer exciton can emerge, in which pairing occurs between constituents that carry fractional charges. Despite numerous theoretical predictions for these fractional excitons, their experimental observation has remained unexplored. Here we report transport signatures of excitonic pairing in fractional quantum Hall effect states. By probing the composition of these excitons and their impact on the underlying wavefunction, we discover two new types of quantum phases of matter. One of these can be viewed as the fractional counterpart of the exciton condensate at a total filling of 1, whereas the other involves a more unusual type of exciton that obeys non-bosonic quantum statistics, challenging the standard model of bosonic excitons.

摘要翻译: 激子，即电子和空穴的库仑驱动束缚态，通常由整数电荷组成。然而，在受电荷分数化影响的双层系统中，可以出现一种更有趣的层间激子形式，其中在携带分数电荷的组分之间发生配对。尽管对这些分数激子有许多理论预测，但它们的实验观察仍未被探索。研究者报道了分数量子霍尔效应态中激子对的运输特征。通过探测这些激子的组成及其对潜在波函数的影响，他们发现了两种新的物质量子相。其中一个可以被看作是总填充为 1 的激子凝聚的分数对应物；而另一个则涉及一种更不寻常的激子类型，它遵循非玻色子量子统计，挑战玻色子激子的标准模型。

文中插图:



[3] Ultrabroadband integrated electro-optic frequency comb in lithium tantalate

钽酸锂中超宽带集成电光频率梳

出版信息: Nature, Volume 637 Issue 8048, 30 January 2025

作者: Junyin Zhang, Chengli Wang, Connor Denney, Johann Riemensberger, Grigory Lihachev, Jianqi Hu, Wil Kao, Terence Blésin, Nikolai Kuznetsov, Zihan Li, Mikhail Churaev, Xin Ou, Gabriel Santamaria-Botello & Tobias J. Kippenberg

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全文链接: <https://www.nature.com/articles/s41586-024-08354-4>

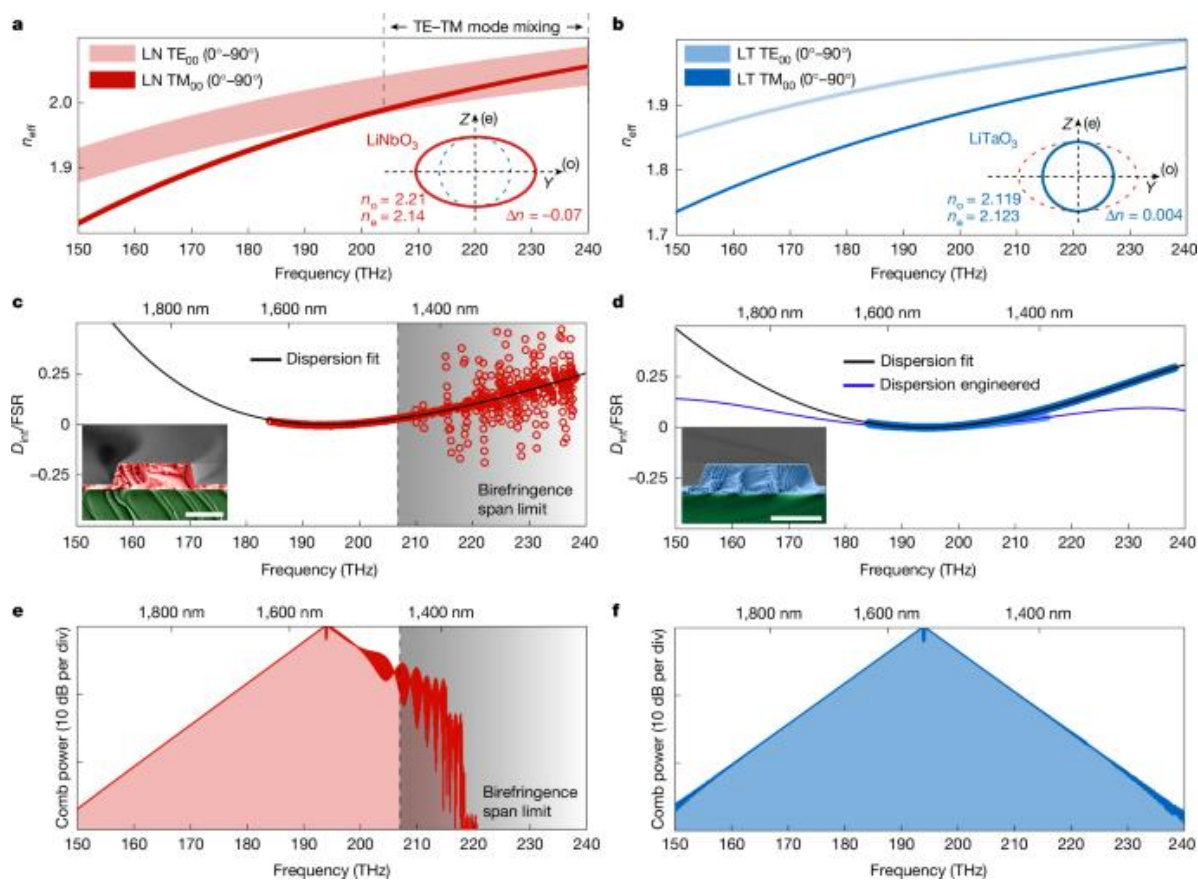
Abstract: The integrated frequency comb generator based on Kerr parametric oscillation¹ has led to chip-scale, gigahertz-spaced combs with new applications spanning hyperscale telecommunications, low-noise microwave synthesis, light detection and ranging, and astrophysical spectrometer calibration. Recent progress in lithium niobate (LiNbO₃) photonic integrated circuits (PICs) has resulted in chip-scale, electro-optic (EO) frequency combs, offering precise comb-line positioning and simple operation without relying on the formation of dissipative Kerr solitons. However, current integrated EO combs face limited spectral coverage due to the large microwave power required to drive the non-resonant capacitive electrodes and the strong intrinsic birefringence of LiNbO₃. Here we overcome both challenges with an integrated triply resonant architecture, combining monolithic microwave integrated circuits with PICs based on the recently emerged thin-film lithium tantalate (LiTaO₃). With resonantly enhanced EO interaction and reduced birefringence in LiTaO₃, we achieve a fourfold comb span extension and a 16-fold power reduction compared to the conventional, non-resonant microwave design. Driven by a hybrid integrated laser diode, the comb spans over 450 nm (more than 60 THz) with more than 2,000 lines, and the generator fits within a compact 1-cm² footprint. We additionally observe that the strong EO coupling leads to an increased comb existence range approaching the full free spectral range of the optical microresonator. The ultra-broadband comb generator, combined with detuning-agnostic operation, could advance chip-scale spectrometry and ultra-low-noise millimetre wave synthesis and unlock octave-spanning EO combs. The methodology of co-designing microwave and photonics can be extended to a wide range of integrated EOs applications.

摘要翻译: 基于 Kerr 参数振荡的集成频率梳发生器已经产生了芯片级、千兆赫间隔的梳, 具有跨超大规模电信、低噪声微波合成、光探测和测距以及天体物理光谱仪校准的新应用。钽酸锂 (LiNbO₃) 光子集成电路 (PICs) 的最新进展推动了芯片规模的电光 (EO) 频率梳, 提供精确的梳线定位和简单的操作, 而不依赖于形成耗散克尔孤子。然而, 由于驱动非谐振电容电极所需的微波功率大, 以及 LiNbO₃ 的强固有双折射, 目前集成 EO



梳子的光谱覆盖范围有限。研究者通过集成三重谐振结构克服了这两个挑战，将单片微波集成电路与基于最近出现的薄膜 LiTaO_3 的 PICs 相结合。与传统的非谐振微波设计相比，通过共振增强的 EO 相互作用和减少的双折射，研究实现了 4 倍的梳子跨度扩展和 16 倍的功率降低。在混合集成激光二极管的驱动下，梳子的跨度超过 450 纳米（超过 60 太赫兹），有 2000 多条线，而发生器的占地面积仅为 1 平方厘米。此外，研究者还观察到强 EO 耦合导致梳子存在范围增加，接近光学微谐振器的全自由光谱范围。超宽带梳状发生器与失谐不确定操作相结合，可以推进芯片级光谱分析和超低噪声毫米波合成，并解锁八度跨度的 EO 梳状器。微波和光子协同设计的方法可以扩展到广泛的集成光电应用。

文中插图：



[4] Moiré-driven topological electronic crystals in twisted graphene

扭曲石墨烯中摩尔驱动的拓扑电子晶体

出版信息: Nature, Volume 637 Issue 8048, 30 January 2025

作者: Ruiheng Su, Dacen Waters, Boran Zhou, Kenji Watanabe, Takashi Taniguchi, Ya-Hui Zhang, Matthew Yankowitz & Joshua Folk

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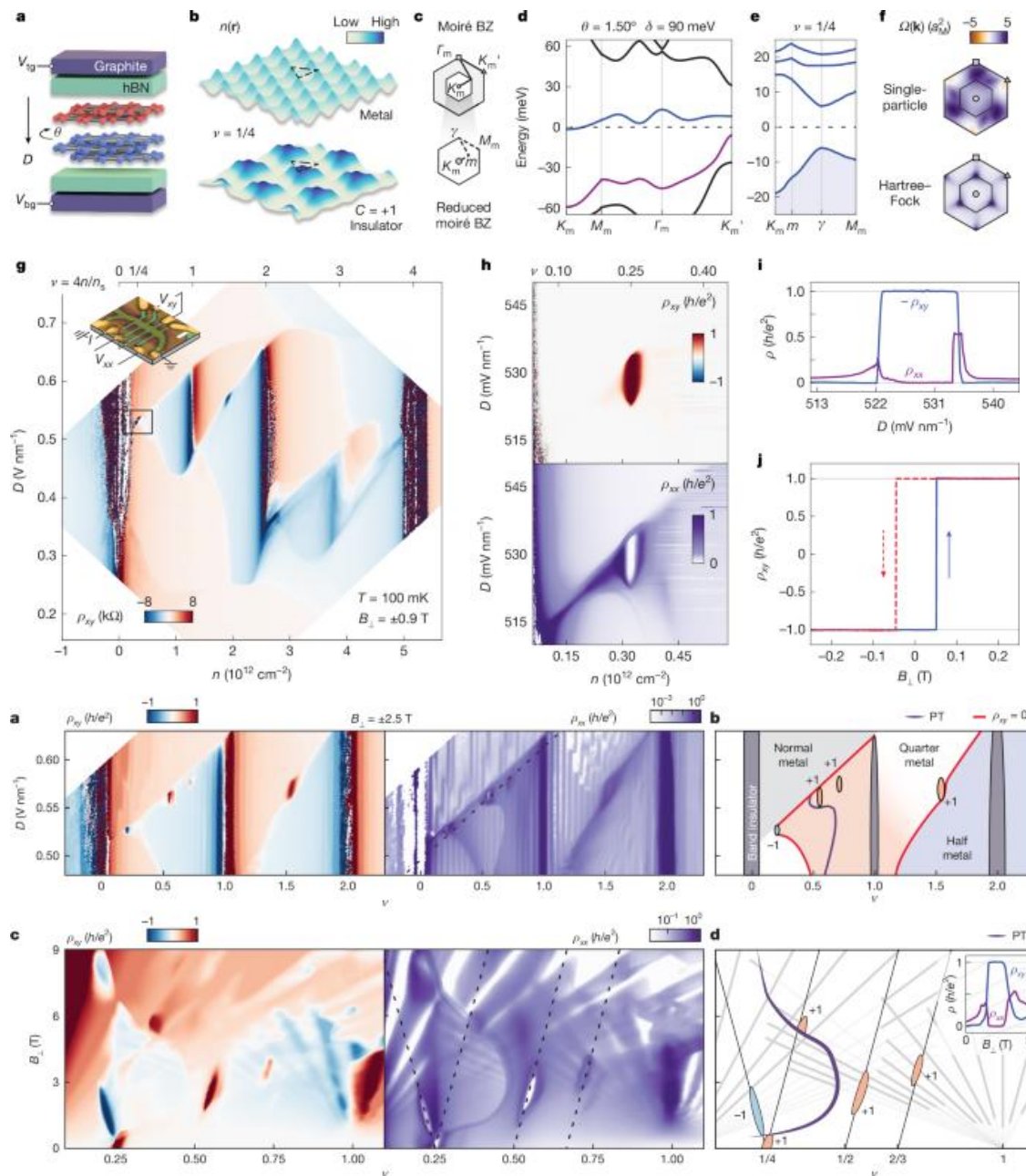
全文链接: <https://www.nature.com/articles/s41586-024-08239-6>

Abstract: In a dilute two-dimensional electron gas, Coulomb interactions can stabilize the formation of a Wigner crystal. Although Wigner crystals are topologically trivial, it has been predicted that electrons in a partially filled band can break continuous translational symmetry and time-reversal symmetry spontaneously, resulting in a type of topological electron crystal known as an anomalous Hall crystal. Here we report signatures of a generalized version of the anomalous Hall crystal in twisted bilayer–trilayer graphene, whose formation is driven by the moiré potential. The crystal forms at a band filling of one electron per four moiré unit cells ($\nu = 1/4$) and quadruples the unit-cell area, coinciding with an integer quantum anomalous Hall effect. The Chern number of the state is exceptionally tunable, and it can be switched reversibly between +1 and -1 by electric and magnetic fields. Several other topological electronic crystals arise in a modest magnetic field, originating from $\nu = 1/3, 1/2, 2/3$ and $3/2$. The quantum geometry of the interaction-modified bands is likely to be very different from that of the original parent band, which enables possible future discoveries of correlation-driven topological phenomena.

摘要翻译: 在稀薄的二维电子气体中, 库仑相互作用可以稳定维格纳晶体的形成。虽然维格纳晶体在拓扑上是微不足道的, 但据预测, 部分填充带中的电子可以自发地打破连续的平移对称性和时间反转对称性, 从而产生一种被称为反常霍尔晶体的拓扑电子晶体。研究者报告了扭曲的双层—三层石墨烯中异常霍尔晶体的广义版本的特征, 其形成是由莫尔阱势驱动的。晶体形成于每 4 个摩尔粒子 ($\nu = 1/4$) 有 1 个电子的带填充, 使单位细胞面积增加了 4 倍, 与整数量子反常霍尔效应相一致。态的陈数是特别可调的, 它可以在电场和磁场的作用下在 +1 和 -1 之间可逆地切换。其他几个拓扑电子晶体出现在适度的磁场中, 起源于 $\nu = 1/3, 1/2, 2/3$ 和 $3/2$ 。相互作用修饰能带的量子几何可能与原始母能带的量子几何非常不同, 这使得可能在未来发现相关驱动的拓扑现象。

文中插图:





[5] Synthesis of a semimetallic Weyl ferromagnet with point Fermi surface

具有点费米表面的半金属 Weyl 铁磁体的合成

出版信息: Nature, Volume 637 Issue 8048, 30 January 2025

作者: Ilya Belopolski, Ryota Watanabe, Yuki Sato, Ryutaro Yoshimi, Minoru Kawamura, Soma Nagahama, Yilin Zhao, Sen Shao, Yuanjun Jin, Yoshihiro Kato, Yoshihiro Okamura, Xiao-Xiao Zhang, Yukako Fujishiro, Youtarou Takahashi, Max Hirschberger, Atsushi Tsukazaki, Kei S. Takahashi, Ching-Kai Chiu, Guoqing Chang, Masashi Kawasaki, Naoto Nagaosa & Yoshinori Tokura

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全文链接: <https://www.nature.com/articles/s41586-024-08330-y>

Abstract: Quantum materials governed by emergent topological fermions have become a cornerstone of physics. Dirac fermions in graphene form the basis for moiré quantum matter and Dirac fermions in magnetic topological insulators enabled the discovery of the quantum anomalous Hall (QAH) effect. By contrast, there are few materials whose electromagnetic response is dominated by emergent Weyl fermions. Nearly all known Weyl materials are overwhelmingly metallic and are largely governed by irrelevant, conventional electrons. Here we theoretically predict and experimentally observe a semimetallic Weyl ferromagnet in van der Waals $(\text{Cr,Bi})_2\text{Te}_3$. In transport, we find a record bulk anomalous Hall angle of greater than 0.5 along with non-metallic conductivity, a regime that is strongly distinct from conventional ferromagnets. Together with symmetry analysis, our data suggest a semimetallic Fermi surface composed of two Weyl points, with a giant separation of more than 75% of the linear dimension of the bulk Brillouin zone, and no other electronic states. Using state-of-the-art crystal-synthesis techniques, we widely tune the electronic structure, allowing us to annihilate the Weyl state and visualize a unique topological phase diagram exhibiting broad Chern insulating, Weyl semimetallic and magnetic semiconducting regions. Our observation of a semimetallic Weyl ferromagnet offers an avenue towards new correlated states and nonlinear phenomena, as well as zero-magnetic-field Weyl spintronic and optical devices.

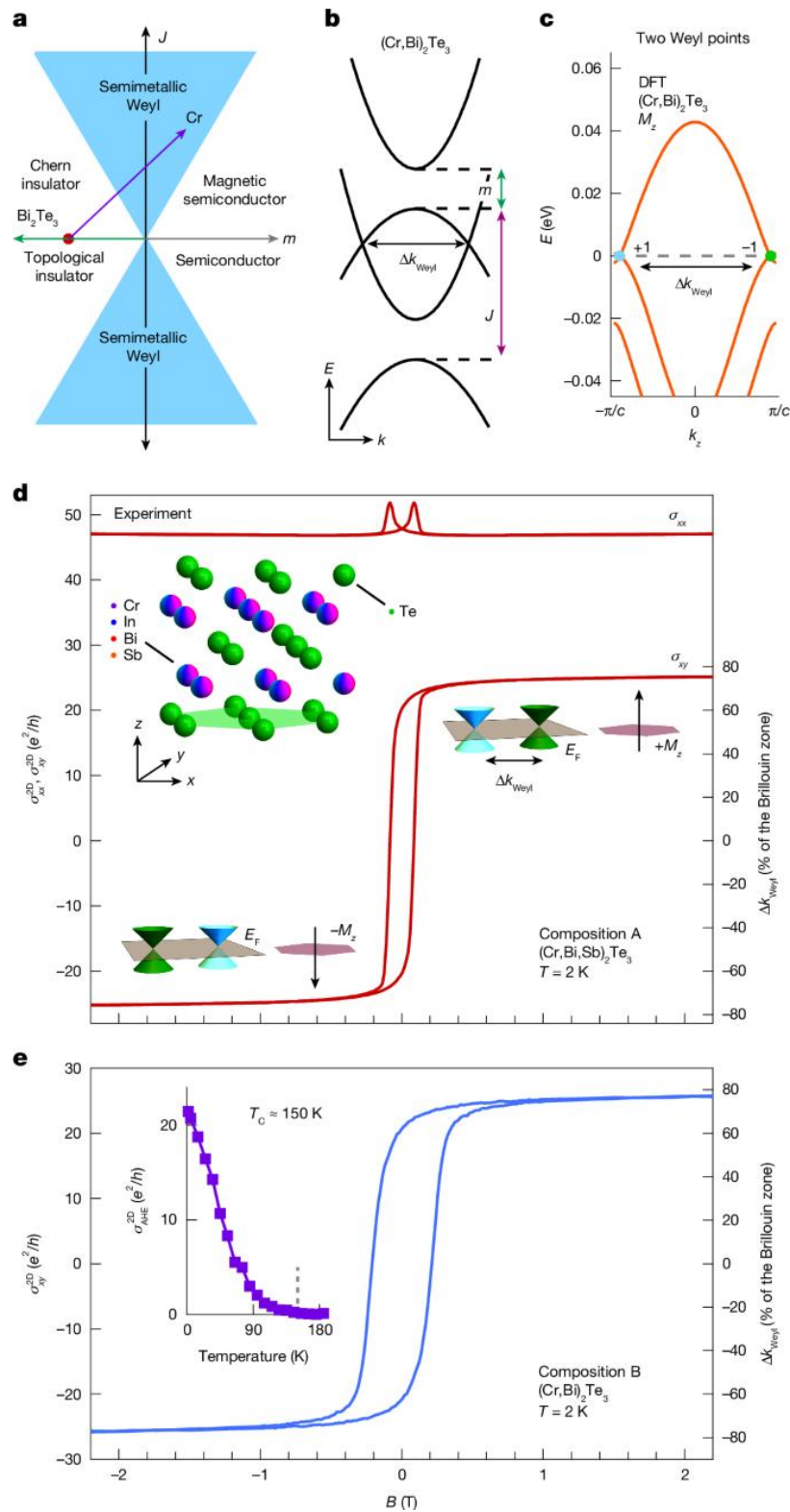
摘要翻译: 由新兴的拓扑费米子控制的量子材料已经成为物理学的基石。石墨烯中的狄拉克费米子构成了摩尔量子物质的基础，磁拓扑绝缘体中的狄拉克费米子使得量子反常霍尔效应 (QAH) 的发现成为可能。相比之下，很少有材料的电磁响应是由涌现的 Weyl 费米子主导的。几乎所有已知的 Weyl 材料绝大多数都是金属，并且在很大程度上由无关的常规电子控制。

这项研究从理论上预测并在实验上观察了范德华 $(\text{Cr,Bi})_2\text{Te}_3$ 中的半金属 Weyl 铁磁体。在输运中，他们发现了一个大于 0.5 的记录体异常霍尔角以及非金属电导率，这是一个与传统铁磁体截然不同的制度。结合对称性分析，研究数据表明一个由两个 Weyl 点组成的半金属费米表面，具有超过体布里渊区线性尺寸 75% 的巨大分离，并且没有其他电子态。

研究者使用最先进的晶体合成技术，广泛调整电子结构，使其能够湮灭 Weyl 状态，并可视化一个独特的拓扑相图，显示广泛的陈氏绝缘，Weyl 半金属和磁性半导体区域。研究者表示，对半金属 Weyl 铁磁体的观察为研究新的相关态和非线性现象以及零磁场 Weyl 自旋电子和光学器件提供了一条途径。



文中插图:



[6] Enhanced energy storage in antiferroelectrics via antipolar frustration

通过反极性挫折增强反铁电体的能量存储

出版信息: Nature, Volume 637 Issue 8048, 30 January 2025

作者: Bingbing Yang, Yiqian Liu, Ru-Jian Jiang, Shun Lan, Su-Zhen Liu, Zhifang Zhou, Lvyue Dou, Min Zhang, Houbing Huang, Long-Qing Chen, Yin-Lian Zhu, Shujun Zhang, Xiu-Liang Ma, Ce-Wen Nan & Yuan-Hua Lin

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Abstract: Dielectric-based energy storage capacitors characterized with fast charging and discharging speed and reliability play a vital role in cutting-edge electrical and electronic equipment. In pursuit of capacitor miniaturization and integration, dielectrics must offer high energy density and efficiency. Antiferroelectrics with antiparallel dipole configurations have been of significant interest for high-performance energy storage due to their negligible remanent polarization and high maximum polarization in the field-induced ferroelectric state. However, the low antiferroelectric–ferroelectric phase-transition field and accompanying large hysteresis loss deteriorate energy density and reliability. Here, guided by phase-field simulations, we propose a new strategy to frustrate antipolar ordering in antiferroelectrics by incorporating non-polar or polar components. Our experiments demonstrate that this approach effectively tunes the antiferroelectric–ferroelectric phase-transition fields and simultaneously reduces hysteresis loss. In PbZrO_3 -based films, we hence realized a record high energy density among all antiferroelectrics of 189 J cm^{-3} along with a high efficiency of 81% at an electric field of 5.51 MV cm^{-1} , which rivals the most state-of-the-art energy storage dielectrics. Atomic-scale characterization by scanning transmission electron microscopy directly revealed that the dispersed non-polar regions frustrate the long-range antipolar ordering, which contributes to the improved performance. This strategy presents new opportunities to manipulate polarization profiles and enhance energy storage performances in antiferroelectrics.

摘要翻译: 介质储能电容器充放电速度快、可靠性高,在尖端电子电气设备中发挥着重要作用。为了追求电容器的小型化和集成化,电介质必须提供高能量密度和效率。具有反平行偶极子结构的反铁电体由于其在场致铁电态中可忽略的剩余极化和高的最大极化而在高性能能量存储中具有重要的意义。然而,低反铁电–铁电相变场和伴随的大磁滞损耗会降低能量密度和可靠性。在相场模拟的指导下,研究者提出了一种新的策略,通过加入非极性或极性成分来挫败反铁电体中的反极性有序。实验表明,该方法有效地调节了反铁电–铁电相变场,同时减小了磁滞损耗。在基于 PbZrO_3 的薄膜中,他们在



5.51 MV cm⁻¹的电场下实现了 189 J cm⁻³的反铁体中创纪录的高能量密度以及 81% 的高效率，可与最先进的储能介质相媲美。扫描透射电子显微镜的原子尺度表征直接揭示了分散的非极性区阻碍了远程反极性有序，有助于提高性能。这种策略为操纵极化分布和提高反铁体的储能性能提供了新的机会。

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