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本期推荐报道 2022 年 4 月 Nature、Science 期刊上物理学领域的部分最新论文。

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物理学 4 月 Science 论文

[1]**A gamma-ray pulsar timing array constrains the nanohertz gravitational wave background**

伽玛射线脉冲星时序阵列限制了纳赫兹引力波背景

出版信息：Science, 29 APR 2022，VOLUME 376 ISSUE 6592

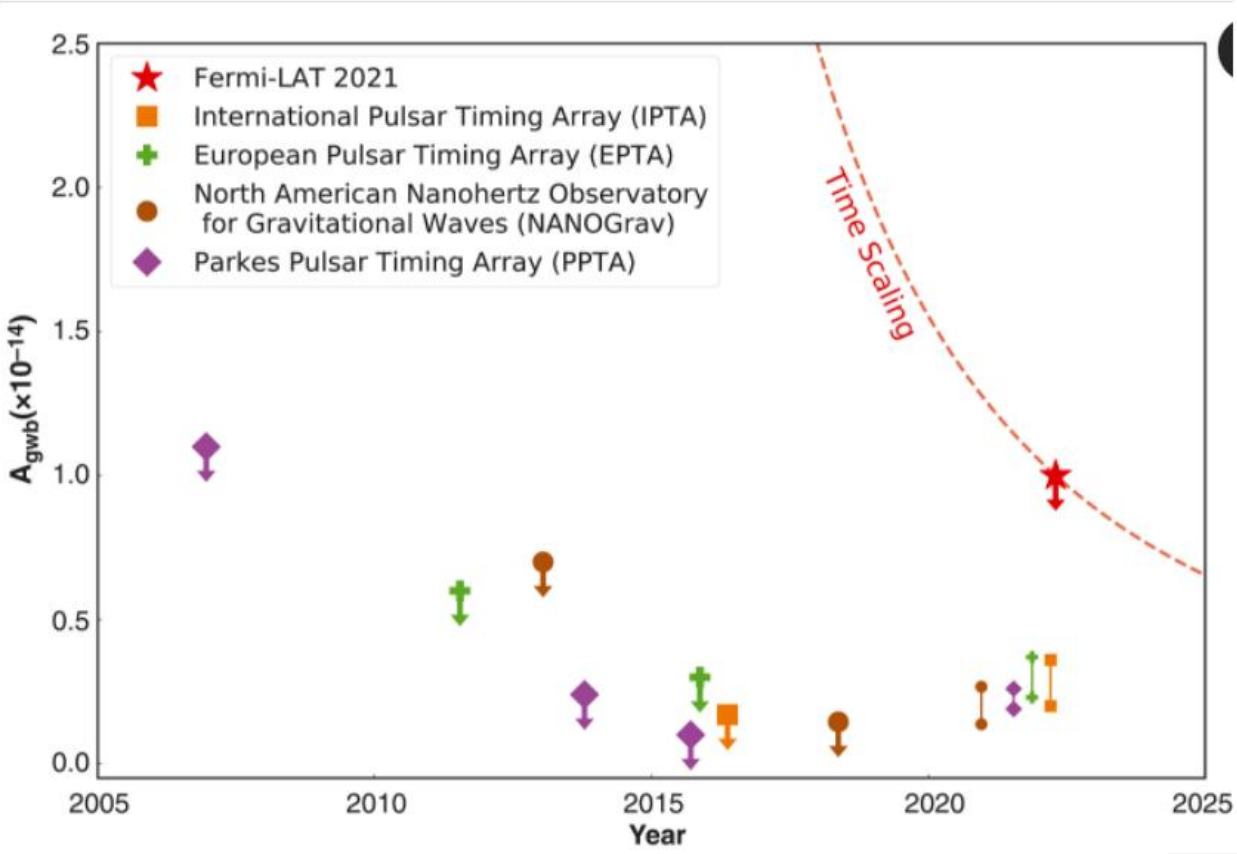
作者：THE FERMI-LAT COLLABORATION

全文链接：https://www.science.org/doi/10.1126/science.abm3231

Abstract：After galaxies merge, the supermassive black holes (SMBHs) at their centers are expected to form binaries that emit gravitational waves at nanohertz frequencies. Numerous SMBH binaries throughout the Universe should combine to produce a gravitational wave background. Existing searches for this signal use radio observations of pulsars as sensitive clocks and look for small shifts in the pulse timings. The Fermi-LAT Collaboration implemented a pulsar timing array using gamma rays and achieved a sensitivity close to that of the radio approaches. The results set an independent upper limit on the gravitational wave background, which is subject to different noise sources.

摘要翻译：星系合并后，中心的超大质量黑洞（SMBHs）或会形成双星，以纳赫兹的频率发射引力波。宇宙中众多的 SMBH 双星应该结合在一起产生引力波背景。目前对这一信号的搜索使用脉冲星的无线电观测作为敏感的时钟，并寻找脉冲时间的微小变化。Fermi-LAT 合作项目利用伽马射线实现了脉冲星计时阵列，并实现了接近无线电接近的灵敏度。结果设置了独立的引力波背景上限，该上限受到不同噪声源的影响。

文中插图：



[2]Superconducting spin smecticity evidencing the Fulde-Ferrell-Larkin-Ovchinnikov state in Sr2RuO4

Sr2RuO4 的超导自旋近晶性证实 Fulde-Ferrell-Larkin-Ovchinnikov 态

出版信息：Science, 22 APR 2022, VOL 376, ISSUE 6591

作者：K. KINJO, M. MANAGO, S. KITAGAWA, Z. Q. MAO, S. YONEZAWA, Y. MAENO, et al.

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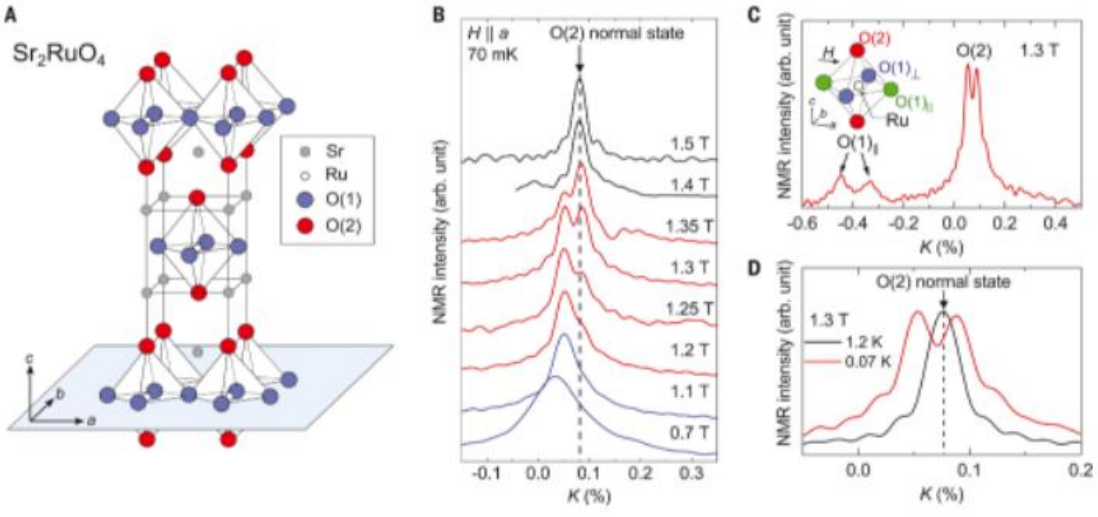
全文链接：https://www.science.org/doi/10.1126/science.abb0332

Abstract：Translational symmetry breaking is antagonistic to static fluidity but can be realized in superconductors, which host a quantum-mechanical coherent fluid formed by electron pairs. A peculiar example of such a state is the Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state, induced by a time-reversal symmetry–breaking magnetic field applied to spin-singlet superconductors. This state is intrinsically accompanied by the superconducting spin smecticity, spin density–modulated fluidity with spontaneous translational-symmetry breaking. Detection of such spin smecticity provides unambiguous evidence for the FFLO state, but its observation has been challenging. Here, we report the characteristic “double-horn” nuclear magnetic resonance spectrum in the layered superconductor Sr2RuO4 near its upper critical field, indicating the spatial sinusoidal modulation of spin density that is consistent with superconducting spin smecticity. Our work reveals that Sr2RuO4 provides a versatile platform for studying FFLO physics.

摘要翻译：平移对称破缺与静态流动性相反，但可以在超导体中实现，超导体是由电子对形成的量子力学相干流体。这种状态的一个特殊例子是 Fulde-Ferrell-Larkin-Ovchinnikov（FFLO）态，由作用于自旋单重态超导体的时间反演对称破缺磁场诱导。FFLO 态本质上伴随着超导自旋近晶性、自旋密度调制流动性和自发平移对称破缺。这种自旋近晶性的检测可为 FFLO 态提供明确证据，但其观测一直颇具挑战性。研究组报道了层状超导体 Sr2RuO4 在其上临界场附近的特征“双喇叭”核磁共振谱，表明自旋密度的空间正弦调制与超导自旋近晶性一致。该研究表明，Sr2RuO4 为研究 FFLO 物理提供了一个多功能平台。

文中插图：



[3]Atomic-scale quantum sensing based on the ultrafast coherence of an H2 molecule in an STM cavity

基于 STM 腔中 H2 分子超快相干性的原子尺度量子传感

出版信息：Science, 22 APR 2022, VOL 376, ISSUE 6591

作者：LIKUN WANG, YUNPENG XIA, AND W. HO

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全文链接：https://www.science.org/doi/10.1126/science.abn9220

Abstract：A scanning tunneling microscope (STM) combined with a pump-probe femtosecond terahertz (THz) laser can enable coherence measurements of single molecules. We report THz pump-probe measurements that demonstrate quantum sensing based on a hydrogen (H2) molecule in the cavity created with an STM tip near a surface. Atomic-scale spatial and femtosecond temporal resolutions were obtained from this quantum coherence. The H2 acts as a two-level system, with its coherent superposition exhibiting extreme sensitivity to the applied electric field and the underlying atomic composition of the copper nitride (Cu2N) monolayer islands grown on a Cu(100) surface. We acquired time-resolved images of THz rectification of H2 over Cu2N islands for variable pump-probe delay times to visualize the heterogeneity of the chemical environment at sub-angstrom scale.

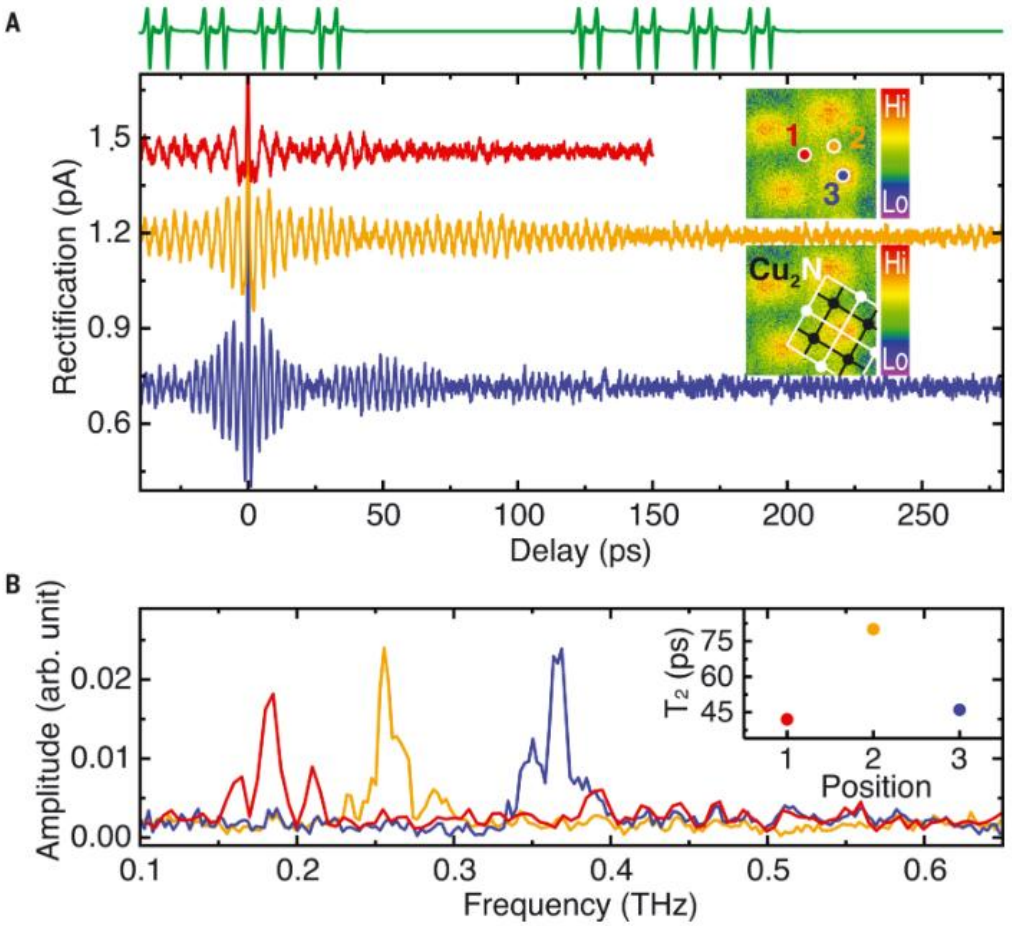
摘要翻译：扫描隧道显微镜（STM）结合泵浦-探针飞秒太赫兹（THz）激光可以实现单分子的相干测量。

研究组报道了太赫兹泵浦-探针测量试验，演示了近表面 STM 针尖在腔中对氢（H2）分子的量子传感。并从这种量子相干性中获得了原子尺度的空间和飞秒时间分辨率。

H2 作为一个二能级系统，其相干叠加对外加电场和生长在 Cu（100）表面的氮化铜（Cu2N）单层岛的底层原子组成表现出极端敏感性。

研究组获得了可变泵浦-探针延迟时间下 H2 在 Cu2N 岛上的太赫兹整流时间分辨图像，实现了亚埃尺度下化学环境异质性的可视化。

文中插图：



[4]**Optical absorption of interlayer excitons in transition-metal dichalcogenide heterostructures**

过渡金属二卤化物异质结层间激子的光吸收

出版信息: Science, 22 APR 2022, VOL 376, ISSUE 6591

作者： ELYSE BARRÉ, OURI KARNI, ERFU LIU, AIDAN L. O’ BEIRNE, XUEQI CHEN, HENRIQUE B. RIBEIRO, et al.

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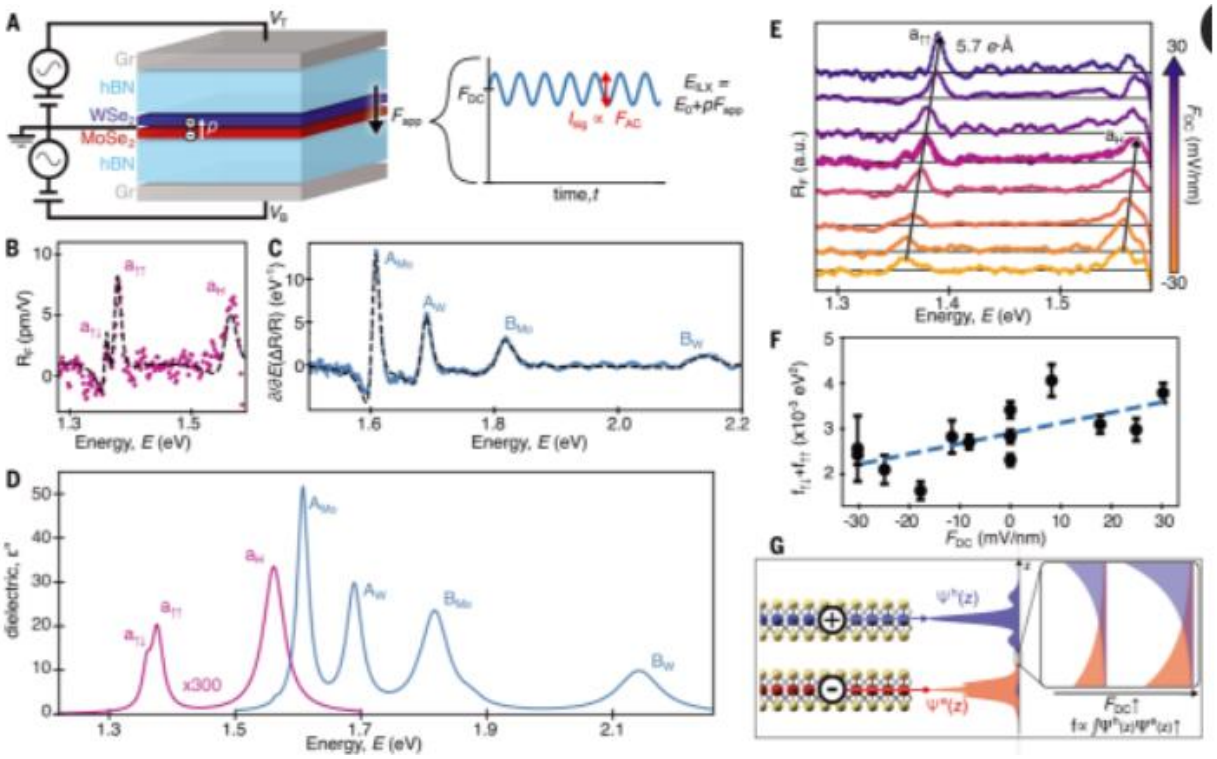
全文链接：https://www.science.org/doi/10.1126/science.abm8511

Abstract： Interlayer excitons, electron-hole pairs bound across two monolayer van der Waals semiconductors, offer promising electrical tunability and localizability. Because such excitons display weak electron-hole overlap, most studies have examined only the lowest-energy excitons through photoluminescence. We directly measured the dielectric response of interlayer excitons, which we accessed using their static electric dipole moment. We thereby determined an intrinsic radiative lifetime of 0.40 nanoseconds for the lowest direct-gap interlayer exciton in a tungsten diselenide/molybdenum diselenide heterostructure. We found that differences in electric field and twist angle induced trends in exciton transition strengths and energies, which could be related to wave function overlap, moiré confinement, and atomic reconstruction. Through comparison with photoluminescence spectra, this study identifies a momentum-indirect emission mechanism. Characterization of the absorption is key for applications relying on light-matter interactions.

摘要翻译：层间激子，即束缚在两个单层范德华半导体上的电子-空穴对，具有良好的电调谐性和局域性。由于此类激子显示出弱电子-空穴重叠，大多数研究仅通过光致发光检测能量最低的激子。研究组直接测量了层间激子的介电响应，通过其静电偶极矩来获取，并确定了二硒化钨/二硒化钼异质结中最低直接间隙层间激子的固有辐射寿命为 0.40 纳秒。该研究发现电场和扭转角的差异会造成激子跃迁强度和能量的变化趋势，这可能与波函数重叠、莫尔约束和原子重构有关。通过与光致发光光谱的比较，研究组确定了一种动量-间接辐射机制。吸收特性是依赖于光-物质相互作用的应用关键。

文中插图：



[5]**High-precision measurement of the W boson mass with the CDF II detector**

高精度测量 W 玻色子的质量

出版信息：Science, 8 APR 2022, VOL 376, ISSUE 6589

作者：T. AALTONENS. AMERIOD. AMIDEIA. ANASTASSOVA. ANNOVIJ. ANTOSG. APOLLINARIJ. A. APPEL, S. ZUCCHELLI, etc.

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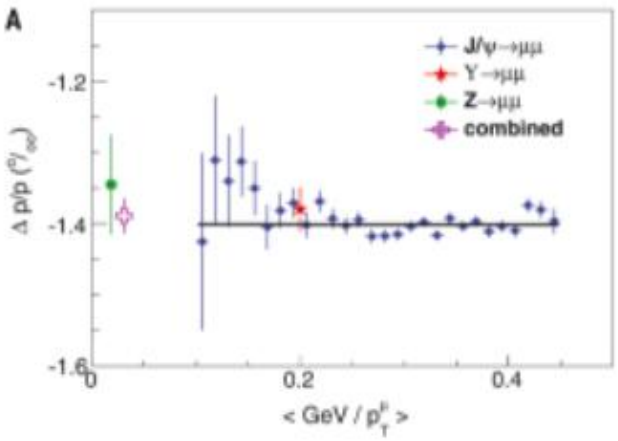
全文链接：https://www.science.org/doi/10.1126/science.abk1781

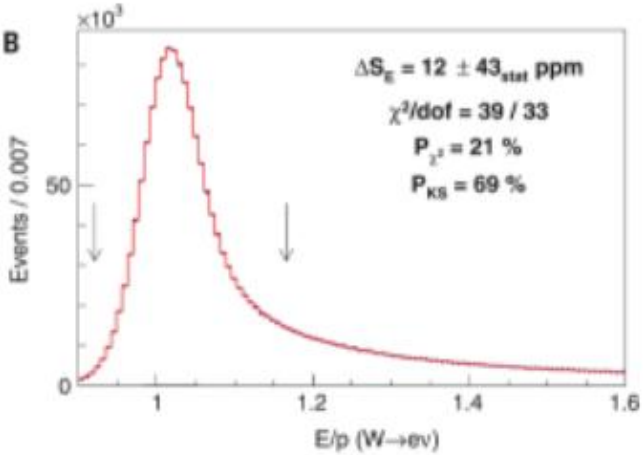
Abstract： W bosons mediate the weak interaction, one of the fundamental forces in physics. Because the Standard Model (SM) of particle physics places tight constraints on the mass of the W boson, measuring the mass puts the SM to the test. The Collider Detector at Fermilab (CDF) Collaboration now reports a precise measurement of the W boson mass extracted from data taken at the Tevatron particle accelerator. Surprisingly, the researchers found that the mass of the boson was significantly higher than the SM predicts, with a discrepancy of 7 standard deviations.

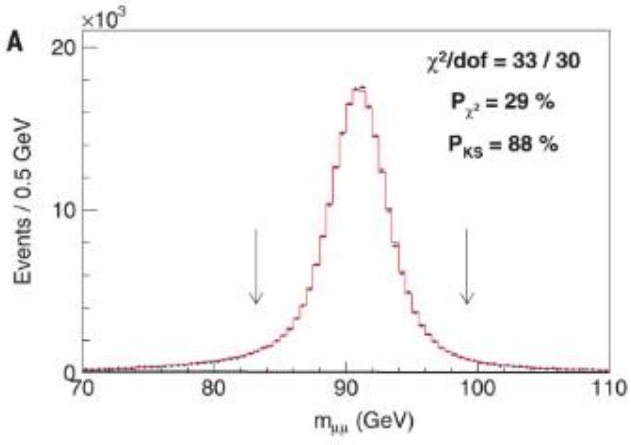
摘要翻译：W 玻色子介导弱相互作用，弱相互作用是物理学中的基本力之一。因为粒子物理学的标准模型 W 玻色子的质量有严格的限制，所以测量质量可以检验标准模型。

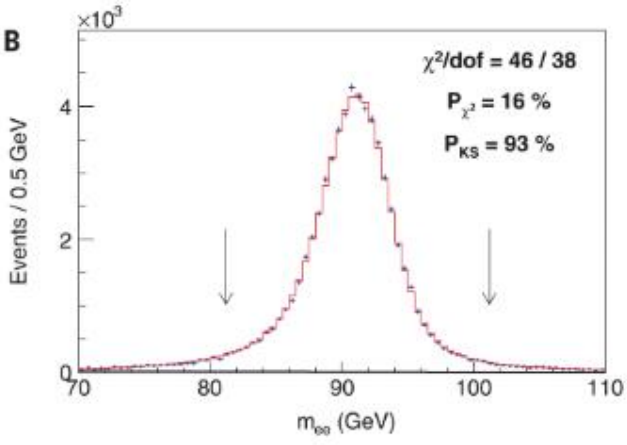
作者利用费米实验室的对撞机探测器（CDF），报告了从太伏质子加速器采集的数据中提取的 W 玻色子质量的精确测量。令人惊讶的是，研究人员发现玻色子的质量明显高于标准模型预测的质量，相差 7 个标准差。

文中插图：









[6]Topological engineering of terahertz light using electrically tunable exceptional point singularities

拓扑光的电气控制

出版信息：Science, 8 APR 2022, VOL 376, ISSUE 6589

作者：M. SAID ERGOKTAS, SINA SOLEYMANI, NURBEK KAKENOV, COSKUN KOCABAS, etc.

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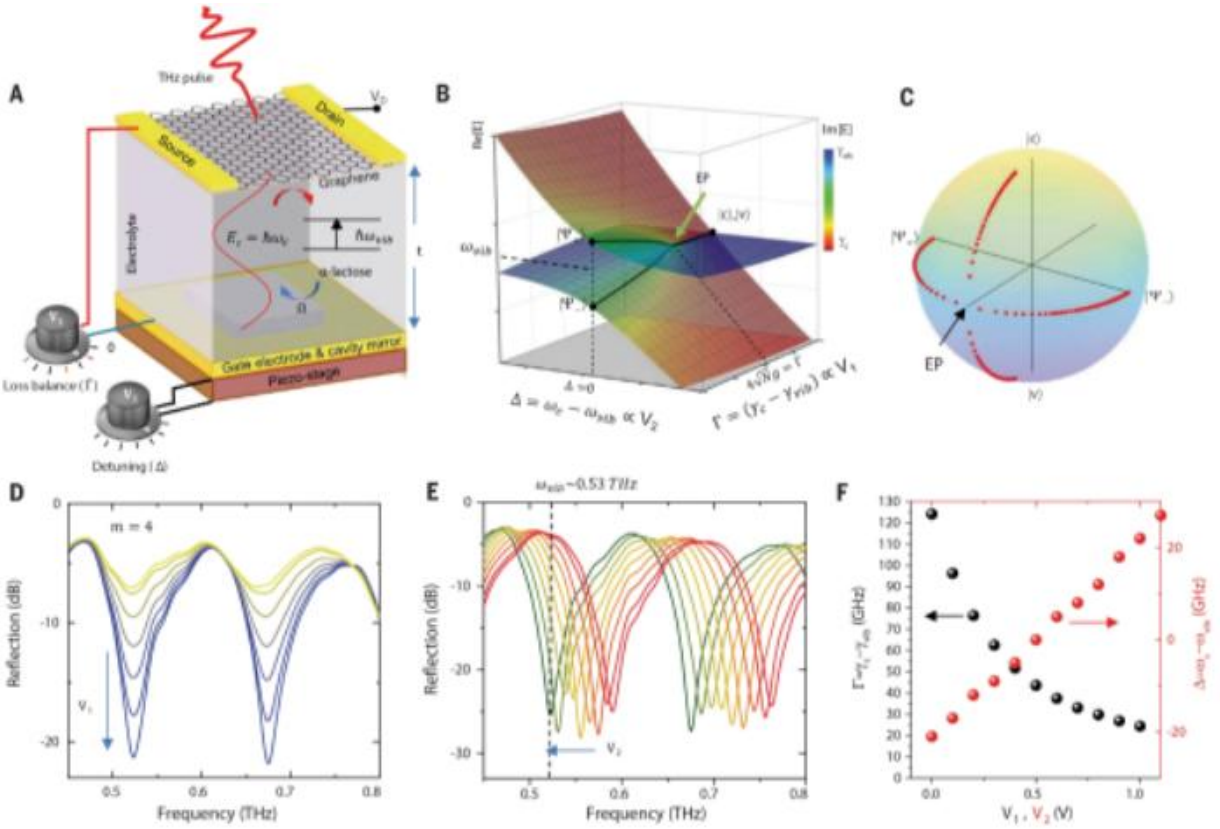
全文链接：https://www.science.org/doi/10.1126/science.abn6528

Abstract： The topological structure associated with the branch point singularity around an exceptional point (EP) can provide tools for controlling the propagation of light. Through use of graphene-based devices, we demonstrate the emergence of EPs in an electrically controlled interaction between light and a collection of organic molecules in the terahertz regime at room temperature. We show that the intensity and phase of terahertz pulses can be controlled by a gate voltage, which drives the device across the EP. Our electrically tunable system allows reconstruction of the Riemann surface associated with the complex energy landscape and provides topological control of light by tuning the loss imbalance and frequency detuning of interacting modes. Our approach provides a platform for developing topological optoelectronics and studying the manifestations of EP physics in light – matter interactions.

摘要翻译：特殊点附近的分支点奇异相关的拓扑结构可以为控制光的传播提供工具。通过使用基于石墨烯的器件，作者证明了在室温下，光和有机分子集合之间的电控制相互作用中 EPs 的出现。他们证明了太赫兹脉冲的强度和相位可以由栅极电压控制，栅极电压驱动器件通过 EP。这一电可调系统可重建与复杂能量景观相关的黎曼表面，并通过调节相互作用模式的损耗不平衡和频率失谐，提供光的拓扑控制。该方法为发展拓扑光电子学和研究极电物理在光物质相互作用中的表现提供了平台。

文中插图：



[7]Orderly disorder in magic-angle twisted trilayer graphene

有序无序的魔角扭曲三层石墨烯

出版信息：Science, 8 APR 2022, VOL 376, ISSUE 6589

作者：SIMON TURKEL, JOSHUA SWANNZIYAN ZHU, MAINE CHRISTOS, K. WATANABE, ABHAY N. PASUPATHY

第一作者单位：Department of Physics, Columbia University, New York, NY 10027, USA.

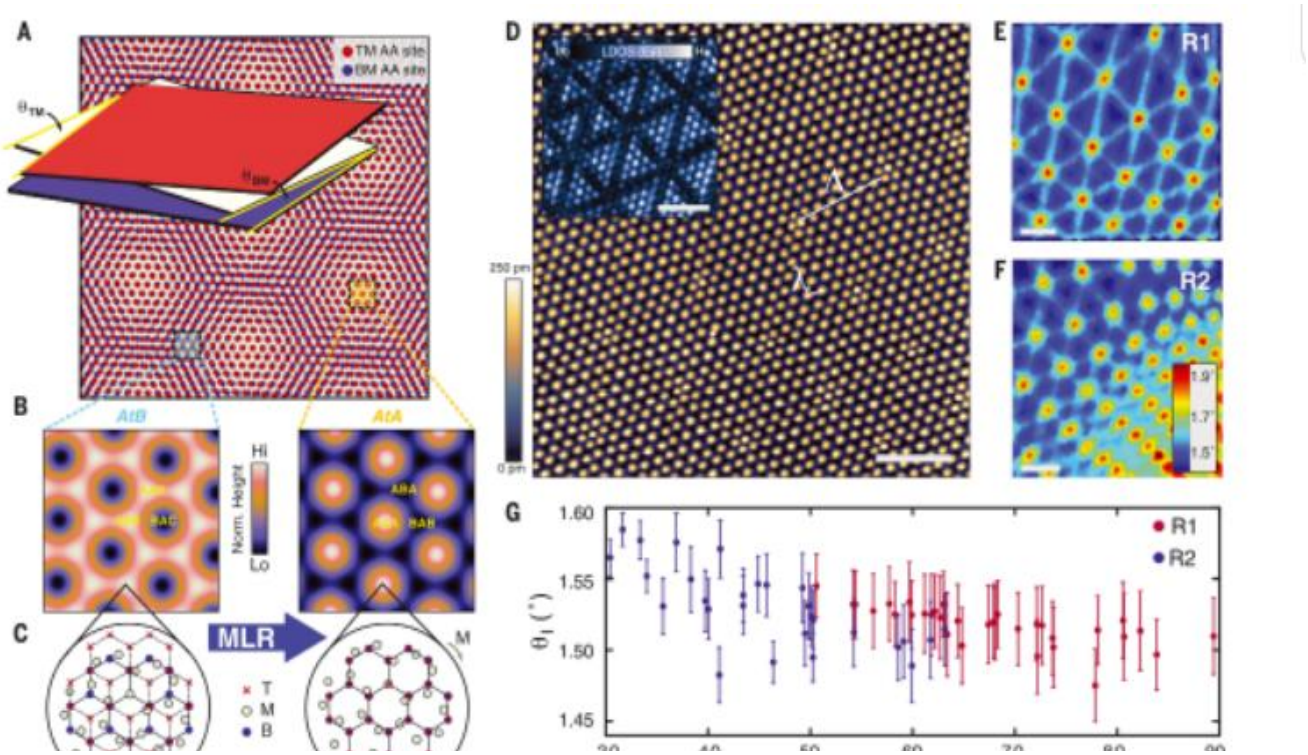
全文链接：https://www.science.org/doi/10.1126/science.abk1895

Abstract： Abstract: Stacking and twisting graphene layers with respect to each other can lead to exotic transport effects. Recently, superconductivity was observed in graphene trilayers in which the top and bottom layers are twisted with respect to the middle layer by the same, “magic” angle. Turkel et al. used scanning tunneling microscopy to take a closer look into the stacking structure. They found that a small misalignment between the top and bottom layers caused the lattice to rearrange itself into a pattern of triangular domains. The domains had a magic-angle twisted trilayer structure and were separated by a network of line and point defects.

摘要翻译：石墨烯层相互堆积和扭曲会导致奇异的输运效应。最近，科学家在石墨烯三层中观察到超导性，其中顶层和底层相对于中间层被相同的“魔术”角度扭曲。作者使用扫描隧道显微镜更仔细地观察堆叠结构。

他们发现，顶层和底层之间的一个微小的错位导致晶格重新排列成三角形域的模式。该魔术具有魔术角扭曲三层结构，并被线和点缺陷网隔开。

文中插图：



[8]**Measurement of a helium tune-out frequency: an independent test of quantum electrodynamics**

量子电动力学的一个独立测试

出版信息：Science, 8 APR 2022, VOL 376, ISSUE 6589

作者：B. M. HENSON, J. A. ROSS, K. F. THOMAS, C. N. KUHN, YONG-HUI ZHANG, LI-YAN TANG, G. W. F. DRAKE, K. G. H. BALDWIN, etc.

第一作者单位：Department of Quantum Science and Technology, Research School of Physics, The Australian National University, Canberra, ACT 2601, Australia.

全文链接：https://www.science.org/doi/10.1126/science.abk2502

Abstract： One of the best ways to advance our understanding of nature is to challenge the fundamental theories developed to describe its laws mathematically. Quantum electrodynamics (QED) theory of the interaction of matter with light is currently one of the most accurate fundamental theories, and the search for QED deviations is of considerable interest. Henson et al. measured and theoretically calculated the helium 23S1 - 23P/33P tune-out frequency with an accuracy that made it possible to discern its QED contributions and previously omitted components. The tune-out frequency is sensitive to a different part of QED compared with other, more common atomic structure probes, and the present work is an important step in expanding the horizon of possible QED tests.

摘要翻译：要增进人们对自然的理解，最好的方法之一就是挑战那些用数学方法描述自然规律的基本理论。光与物质相互作用的量子电动力学（QED）理论是目前最精确的基础理论之一，对 QED 偏差的研究是目前研究的热点。作者测量并从理论上计算了氦 23S1 - 23P/33P 调谐频率，其精度使其 QED 贡献和之前忽略的分量成为可能。与其他更常见的原子结构探针相比，调谐输出频率对 QED 的不同部分敏感，因此这样工作是扩展 QED 可能测试范围的重要一步。

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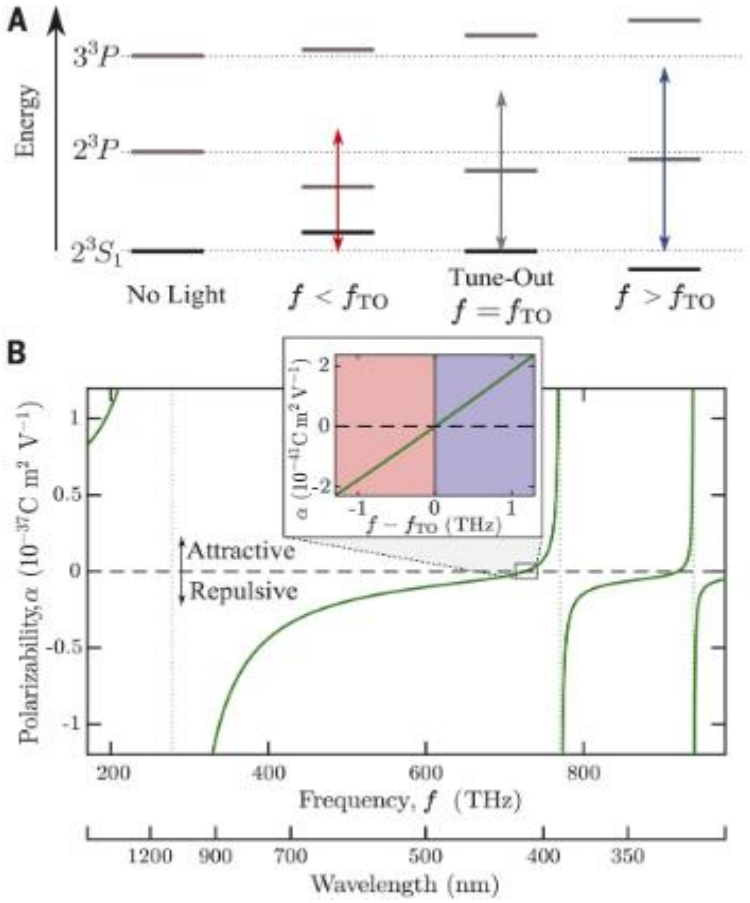

[1]Observation of a linked-loop quantum state in a topological magnet

拓扑磁体中链环量子态的观察

出版信息：Nature, 28 April 2022, Volume 604 Issue 7907

作者：Ilya Belopolski, Guoqing Chang, Tyler A. Cochran, Zi-Jia Cheng et al.

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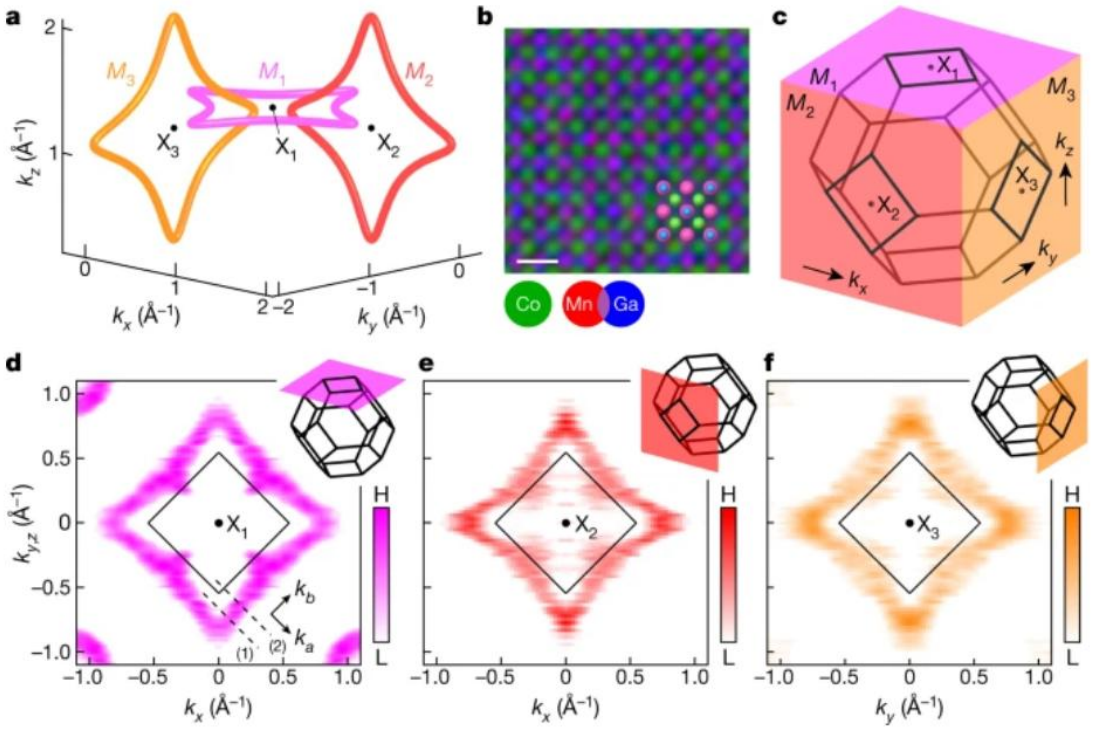
RIKEN Center for Emergent Matter Science (CEMS), Wako, Saitama, Japan

全文链接：https://www.nature.com/articles/s41586-022-04512-8

Abstract：Here we report an unusual linking-number (knot theory) invariant associated with loops of electronic band crossings in a mirror-symmetric ferromagnet. Using state-of-the-art spectroscopic methods, we directly observe three intertwined degeneracy loops in the material’s three-torus, T3, bulk Brillouin zone. We find that each loop links each other loop twice. Through systematic spectroscopic investigation of this linked-loop quantum state, we explicitly draw its link diagram and conclude, in analogy with knot theory, that it exhibits the linking number (2, 2, 2), providing a direct determination of the invariant structure from the experimental data. We further predict and observe, on the surface of our samples, Seifert boundary states protected by the bulk linked loops, suggestive of a remarkable Seifert bulk–boundary correspondence. Our observation of a quantum loop link motivates the application of knot theory to the exploration of magnetic and superconducting quantum matter.

摘要翻译：在此，我们报告一个与在镜像对称铁磁体中电子带交叉环线相关的不寻常的连接数（扭结理论）不变量。利用最先进的光谱方法，我们直接观察到材料的三环体 T3 布里渊区中三个纠缠在一起的简并环。我们发现每个环连接其他环两次。通过系统光谱研究这一链环量子态，我们明确地画出了它的链图，并类比结理论，得出它的链数为(2,2,2)，从实验数据直接确定了它的不变结构。我们进一步预测和观察了样品表面的塞弗特边界态，该边界态由体链环保护，表明了显著的塞弗特体边界响应。我们对量子环链的观察，推动了扭结理论在探索磁性和超导量子物质方面的应用。

文中插图：



[2]The field-free Josephson diode in a van der Waals heterostructure

范德华异质结构中的无磁场约瑟夫森二极管

出版信息：Nature, 28 April 2022, Volume 604 Issue 7907

作者：Heng Wu, Yaojia Wang, Yuanfeng Xu, Pranava K. Sivakumar, Chris Pasco, Ulderico Filippozzi, Stuart S. P. Parkin, Yu-Jia Zeng, Tyrel McQueen & Mazhar N. Ali

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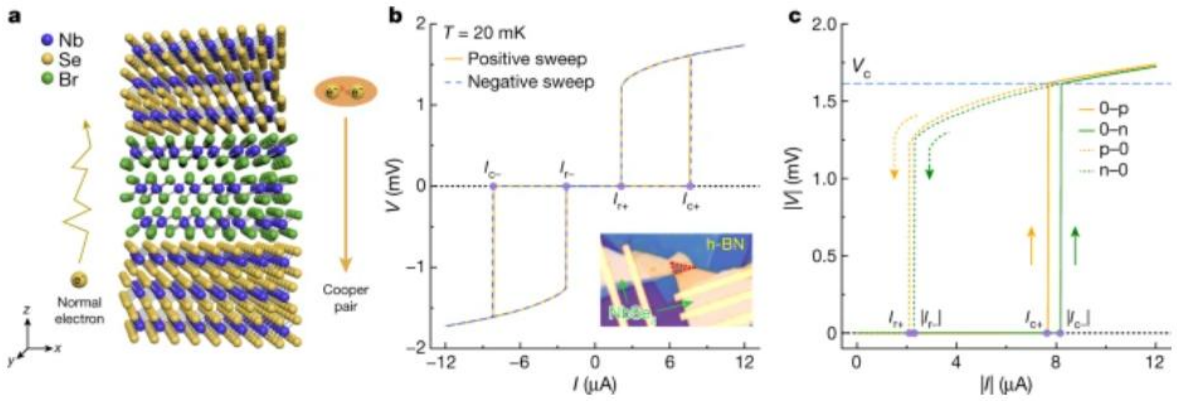
全文链接：https://www.nature.com/articles/s41586-022-04504-8

Abstract：Here we realized the Josephson diode by fabricating an inversion symmetry breaking van der Waals heterostructure of NbSe2/Nb3Br8/NbSe2. We demonstrate that even without a magnetic field, the junction can be superconducting with a positive current while being resistive with a negative current. The ΔIc behaviour (the difference between positive and negative critical currents) with magnetic field is symmetric and Josephson coupling is proved through the Fraunhofer pattern. Also, stable half-wave rectification of a square-wave excitation was achieved with a very low switching current density, high rectification ratio and high robustness. This non-reciprocal behaviour strongly violates the known Josephson relations and opens the door to discover new mechanisms and physical phenomena through integration of quantum materials with Josephson junctions, and provides new avenues for superconducting quantum devices.

摘要翻译：在此，我们通过制作 NbSe2/Nb3Br8/NbSe2 的反转对称破缺范德华异质结构，实现了约瑟夫森二极管。我们证明，即使没有磁场，结也可以在正电流下超导，同时在负电流下具有电阻性。ΔIc 行为（正和负临界电流之间的差异）与磁场是对称的，约瑟夫逊耦合可以通过夫劳恩霍夫模式证明。同时，我们以极低的开关电流密度、高整流比和高鲁棒性实现了方波激励的稳定半波整流。这种非互易行为强烈违背了已知的约瑟夫森关系，并为通过量子材料与约瑟夫森结的整合打开了发现新的机制和物理现象的大门，并为超导量子器件提供了新的途径。

文中插图：



[3]Intelligent infrared sensing enabled by tunable moiré quantum geometry

可调谐莫尔量子几何实现智能红外传感

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全文链接：https://www.nature.com/articles/s41586-022-04548-w

Abstract：Quantum geometric properties of Bloch wave functions in solids, that is, Berry curvature and the quantum metric, are known to significantly influence the ground- and excited-state behaviour of electrons. The bulk photovoltaic effect (BPVE), a nonlinear phenomenon depending on the polarization of excitation light, is largely governed by the quantum geometric properties in optical transitions. Infrared BPVE has yet to be observed in graphene or moiré systems, although exciting strongly correlated phenomena related to quantum geometry have been reported in this emergent platform. Here we report the observation of tunable mid-infrared BPVE at 5 μm and 7.7 μm in twisted double bilayer graphene (TDBG), arising from the moiré-induced strong symmetry breaking and quantum geometric contribution. The photoresponse depends substantially on the polarization state of the excitation light and is highly tunable by external electric fields. This wide tunability in quantum geometric properties enables us to use a convolutional neural network to achieve full-Stokes polarimetry together with wavelength detection simultaneously, using only one single TDBG device with a subwavelength footprint of merely 3 × 3 μm2. Our work not only reveals the unique role of moiré engineered quantum geometry in tunable nonlinear light–matter interactions but also identifies a pathway for future intelligent sensing technologies in an extremely compact, on-chip manner.

摘要翻译：众所周知，固体中布洛赫波函数的量子几何性质，即贝里曲率和量子度量，显著影响着电子的基态和激发态行为。

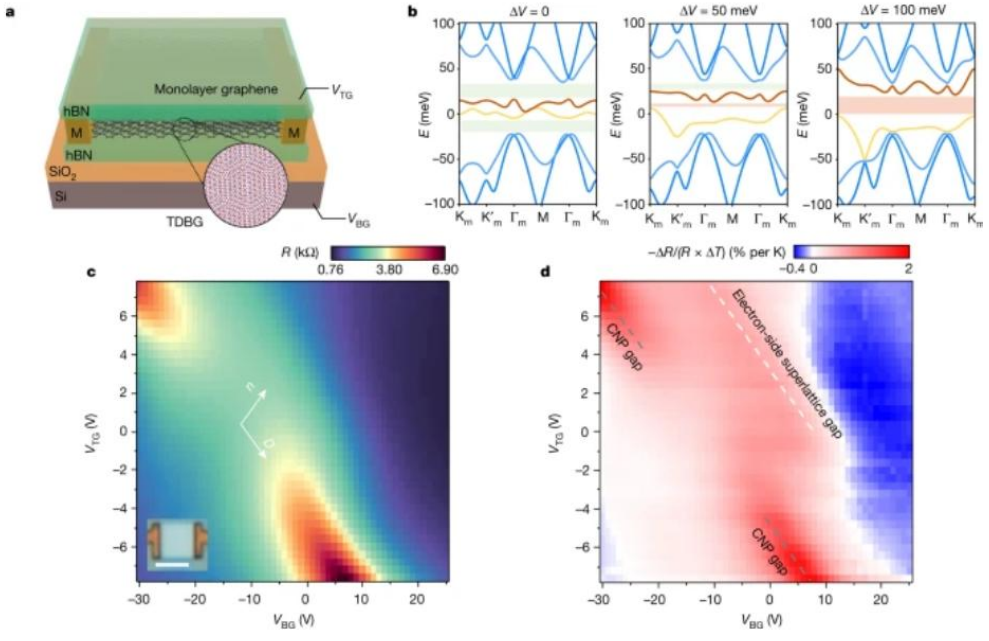
体光伏效应（BPVE）是一种依赖于激发光偏振的非线性现象，在很大程度上取决于光学跃迁中的量子几何特性。红外 BPVE 尚未在石墨烯或莫尔体系等新兴平台中观察到，尽管这些平台已报道过与量子几何有关的激发强关联现象。

研究组报道了在扭曲双双层石墨烯（TDBG）中观察到 5 μm 和 7.7 μm 处可调谐中红外 BPVE，由莫尔诱导的强对称性破缺和量子几何贡献产生。光响应在很大程度上取决于激发光的偏振态，且可通过外部电场进行高度调谐。

这种量子几何特性的广泛可调性使研究组能够使用卷积神经网络同时实现全斯托克斯偏振测量和波长检测，仅使用一个亚波长足迹仅为 3× 3 μm2 的 TDBG 器件 。

该研究工作不仅揭示了莫尔工程量子几何在可调谐非线性光-物质相互作用中的独特作用，还以极其紧凑的芯片方式为未来智能传感技术开辟了新途径。

文中插图：



[4]Search for Majorana neutrinos exploiting millikelvin cryogenics with CUORE

利用极低温环境晶体寻找马约拉纳中微子

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全文链接：https://www.nature.com/articles/s41586-022-04497-4

Abstract: Here we show results from the search for 0νββ decay of ^{130}Te, using the latest advanced cryogenic calorimeters with the CUORE experiment. CUORE, operating just 10 millikelvin above absolute zero, has pushed the state of the art on three frontiers: the sheer mass held at such ultralow temperatures, operational longevity, and the low levels of ionizing radiation emanating from the cryogenic infrastructure. We find no evidence for 0νββ decay and set a lower bound of the process half-life as 2.2×1025years at a 90 per cent credibility interval. We discuss potential applications of the advances made with CUORE to other fields such as direct dark matter, neutrino and nuclear physics searches and large-scale quantum computing, which can benefit from sustained operation of large payloads in a low-radioactivity, ultralow-temperature cryogenic environment.

摘要翻译：在此，我们展示了最新的低温器和 CUORE 实验对 130Te 晶体中无中微子双贝塔衰变的搜索结果。CUORE 实验的运行温度仅比绝对零度高 10 毫微，它在三个方面提高了将技术前沿：超低温度下的质量、运行寿命和低温基础设施产生的低水平电离辐射。

结果表明，无中微子双贝塔在 90%的可信区间内没有出现衰变现象，且其半衰期下限为 2.2×1025 年。我们讨论了 CUORE 在其他领域的潜在应用进展，如直接暗物质、中微子和核物理搜索以及大规模量子计算，这得益于在低放射性、超低温低温环境中持续运行的大规模有效载荷。

文中插图：