中国科学: 物理学 力学 天文学 2026 年 第 56 卷 第 2 期: 227503
SCIENTIA SINICA Physica, Mechanica & Astronomica physcn.scichina.com
《中国科学》杂志社 SCIENCE CHINA PRESS
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评 述 磁性随机存储器专题

交错磁体的研究进展与未来展望

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收稿日期: 2024-11-23; 接受日期: 2025-01-17; 网络出版日期: 2025-06-04
国家自然科学基金(编号: 523B1007, 52225106, 12241404, T2394471)和国家重点研发计划(编号: 2022YFA1402603)资助项目

摘要 交错磁体在实空间中具有交错的共线补偿自旋排布, 倒空间中具有交错的能带自旋劈裂, 被认为是一种新型的磁性相. 它融合了铁磁与反铁磁的双重优势. 其独特特性包括: 无杂散场、高本征磁动力学频率, 以及时间反演对称性破缺而导致的非平庸磁响应. 此外, 交错磁体广泛分布于金属、半导体、绝缘体和超导体等多种材料体系中, 为其研究提供了深远的内涵和多维的探索空间. 本综述从对称性出发, 明确了交错磁体与传统铁磁、反铁磁材料的本质区别, 并列举了典型的交错磁体材料. 进一步地, 系统梳理了交错磁体领域的最新实验进展, 涵盖交错磁体中与自旋劈裂相关的输运行为和对交错磁体自旋劈裂的调控. 最后, 对交错磁体的未来研究方向进行了展望, 重点包括基于交错磁体的高性能自旋存储器件构筑、交错磁体自旋劈裂的实空间成像、交错磁体与准粒子的耦合以及交错磁体与多铁态的结合等多个领域. 这些前景表明, 作为自旋电子学方向的全新研究领域, 交错磁体材料在未来具有广阔的应用潜力和重要的科学价值.

关键词 交错磁体, 交错磁性, 自旋劈裂, 对称性破缺, 自旋电子学

PACS: 72.25.Ba, 72.25.Dc, 75.50.Ee, 81.05.Bx, 85.75.Dd

1 引言

交错磁体是近年来磁学与磁性材料领域提出的一种新型磁性相[1–3]. 在磁结构上, 交错磁体与传统反铁磁材料类似[4,5], 内部磁矩相互补偿, 在非相对论极限下净磁矩为零, 抗外磁场干扰能力强, 磁动力学频率可达太赫兹量级; 而在能带结构上, 交错磁体具有非简并的自旋能带, 可以产生类似于铁磁材料中的自旋劈裂效应, 以及时间反演对称性破缺相关的一系列非平庸磁响应, 如反常霍尔效应[6]和隧穿磁电阻效应[7,8]. 作为区别于传统铁磁与反铁磁材料的新型磁性材料, 交错磁体兼具上述二者的优势, 其基础理论与器件应用的研究已成为近年来自旋电子学研究的热点话题之一[1–3,6,9–21]. 近期, "一种新型的磁性——交错磁性的发现"入选《科学》2024年度十大科学突破[22], 这表明交错磁体研究主题已经得到了学术界的广泛认可.

本文首先从对称性的角度给出了交错磁体的定义, 并基于此讨论总结了几种典型的交错磁体材料. 这些材料中的自旋劈裂特征已在实验上得到谱学或输运上的证实. 随后, 我们梳理了交错磁体的最新研究进

引用格式: 戴健坤, 韩磊, 周致远, 等. 交错磁体的研究进展与未来展望. 中国科学: 物理学 力学 天文学, 2026, 56: 227503
Dai J K, Han L, Zhou Z Y, et al. Research progress and future prospects of altermagnets (in Chinese). Sci Sin-Phys Mech Astron, 2026, 56: 227503, doi: 10.1360/SSPMA-2024-0564

展: (1) 自旋劈裂相关的输运行为, 包括依赖于自旋-轨道耦合的反常霍尔效应、反常能斯特效应等以及不依赖于自旋-轨道耦合的自旋-电荷转化和隧穿磁电阻效应等; (2) 自旋劈裂的调控, 包括利用自旋-轨道力矩实现奈尔矢量180°翻转以及利用应力调控交错磁体磁空间群等. 最后, 本文从基础研究与器件应用的角度, 讨论了交错磁体的未来发展方向, 涵盖基于交错磁体的新型自旋存储器件构筑、自旋劈裂的实空间成像、交错磁体与准粒子的耦合以及多铁材料与交错磁体的结合. 这些展望为交错磁体的深入研究和应用提供了重要启示.

2 交错磁体的对称性分析

磁性与自旋是相辅相成的概念, 磁性材料是自旋电子学研究的基本出发点. 根据磁结构分类, 磁性材料主要包括铁磁(亚铁磁)和反铁磁两大类. 铁磁材料因宏观磁化打破时间反演对称性, 其能带在倒空间的各点均发生塞曼劈裂(图1(a)); 而在传统共线反铁磁材料中, 相邻自旋相反的原子保持了时间反演操作(T)与空间操作(包括平移操作t或者空间反演操作P)联合对称性, 从而在动量空间的每一个点都严格自旋简并(图1(b)).

在传统的磁学观点中, 铁磁材料与反铁磁材料的特征互相排斥, 泾渭分明. 然而, 近年来理论计算表明, 部分共线反铁磁材料(如RuO_2[6,9], κ-Cl[10], MnF_2[11], $LaMnO_3$[11], $FeSb_2$[14], V_2Se_2O[15])中, 携带相反自旋的磁性原子周围的非磁原子环境不同. 这种差异引发了晶体场的各向异性, 从而导致动量空间产生交错的能带自旋劈裂, 并展现旋转对称性(图1(c)). 针对这些兼具共线反铁磁序和能带自旋劈裂的特殊反铁磁, 可以用自旋空间群的方式进行描述[1,2,16]. 具体来说, 磁性材料体系中的自旋空间群形式为$[R_i||R_j]$, 其中对称操作R_i用于刻画磁性原子的自旋对称性, R_j则描述晶体学对称性. 从自旋空间群的角度出发, 对于传统的共线反铁磁, 携带相反自旋的磁性原子周围的非磁原子环境相同, 具有PT或者tT对称性, 因而动量空间自旋高度简并; 而在某些非常规共线反铁磁结构中, 由于磁性原子周围的非磁原子打破了中心反演对称性, 体系的PT或者tT对称性失效, 相反自旋只能通过对称操作CT进行连接[15], 其中对称操作C表示旋转、镜面、滑移、螺旋等非平移、非反演的空间操作. 这种对称性导致自旋向上和向下的能带在动量空间上整体补偿, 但在部分低对称点上出现交错劈裂[1–3] (图1(c)). 由于上述劈裂来源于电子自旋的交换相互作用而非自旋-轨道耦合, 故劈裂的大小可与铁磁材料相当[1,2,6].

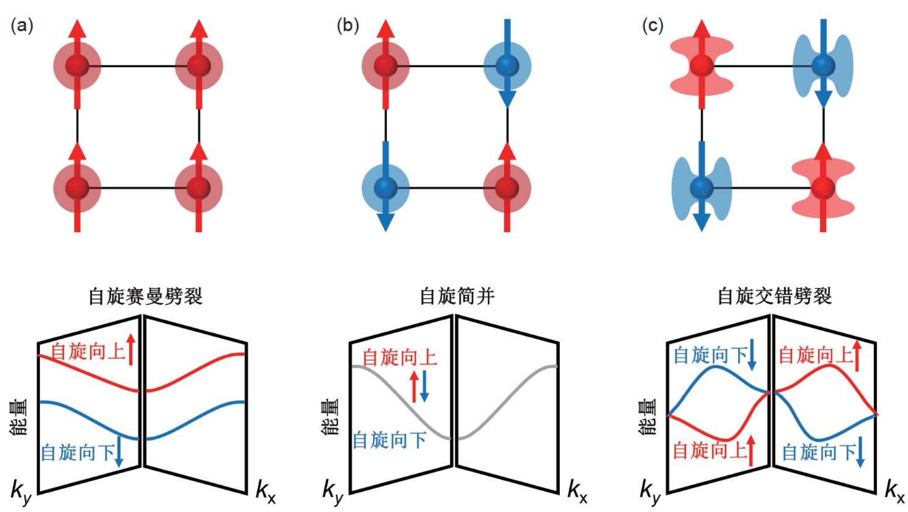

图 1 (网络版彩图)铁磁、反铁磁以及交错磁性的比较. (a) 铁磁性材料在实空间的磁矩分布及对应动量空间中的自旋塞曼劈裂; (b) 反铁磁性材料在实空间的磁矩分布及对应动量空间中的自旋简并; (c) 交错磁体在实空间的磁矩分布对应动量空间中的自旋交错劈裂

Figure 1 (Color online) Comparison of ferromagnets, antiferromagnets, and altermagnets. (a) Magnetic moments alignment in real space and spin Zeeman splitting in momentum space for ferromagnets; (b) magnetic moments alignment in real space and spin degeneracy in momentum space for antiferromagnets; (c) magnetic moments alignment in real space and staggered spin splitting in momentum space for altermagnets.

从自旋空间群的角度，这类磁性材料具有不同于铁磁和反铁磁的对称性，被称为交错磁体(Altermagnet). 交错磁体的发现不仅催生了一系列揭示新奇物理现象的理论与实验研究，展现了构筑新型自旋电子学器件的巨大潜力(详见后文)，还引发了对磁性材料对称性的新讨论: Cheong和Huang从磁点群角度指出，尽管交错磁体破缺*PT*对称性，其磁点群仍包含在传统铁磁与反铁磁磁点群中，这一分析可进一步推广至非共线反铁磁体系[17]；近期的几篇研究工作对现有磁性材料体系进行了重新梳理，将铁磁、反铁磁、非共线反铁磁和交错磁体统一于自旋空间群对称性描述，从对称性上对磁结构进行了较为系统的描述[18–20]. 此外，Bhowal和Spaldin指出，对于如MnF_2等具有*d*波劈裂的交错磁体，其时空反演对称破缺可通过磁八极子进行描述[21]. 这些研究表明，交错磁体与传统磁性相之间的关联仍在不断探索和深入发展之中.

此外还需要强调的是，能带自旋劈裂不仅存在于具有共线磁矩的交错磁体中，还广泛存在于各种非共线反铁磁材料体系中，例如Mn_3Sn[23]，Mn_3Ge[24]等. 而在最近的研究工作中，研究人员成功利用角分辨光电子谱(Angle Resolved Photoemission Spectroscopy, ARPES)实现了对于非共线反铁磁材料$MnTe_2$自旋劈裂能带的观测与表征[25]，进一步丰富了人们对于磁矩补偿体系中自旋劈裂现象的认识.

3 交错磁体材料

交错磁体材料涵盖金属、半导体、绝缘体和超导体等多种体系，不仅为材料物理和凝聚态物理的基础研究开辟了新领域，也为新型自旋电子学器件的开发注入了新活力. 在三维材料体系中，金红石相RuO_2[26]、六方相α-MnTe[27]和CrSb[28]是代表性材料，其具有较大的自旋劈裂能和较高的奈尔温度(图2). 除此之外，六方相Mn_5Si_3薄膜也被认为是交错磁体的候选材料而受到广泛关注[29–33]. 理论计算表明，交错磁性还可存在于有机[10]以及二维材料体系[15,34]. 特别是通过扭转堆叠单层二维材料[35,36]，可构建人工交错磁体. 这些材料的未来研究将推动柔性与可堆叠自旋电子学器件的发展.

自旋能带在倒空间交错劈裂是交错磁体材料区别于其他磁性材料的本质特征之一，而APERS技术则是探测上述能带劈裂结构的重要手段，可以用于表征各类交错磁体在动量空间中的自旋能带劈裂，从而证实材料体系中交错磁性的存在. 目前主要使用的手段包括软X射线ARPES (Soft X-Ray ARPES, SX-ARPES)[37]、自旋分辨ARPES (Spin-Resolved ARPES, SARPES)[38]以及磁光二色ARPES (Magnetic Dichroism ARPES, MD-ARPES)[26]三种. 基于上述技术，研究人员已成功在三维交错磁体RuO_2[26]，α-MnTe[27,39–41]，CrSb[28,42–46]以及二维交错磁体材料，例如Rb掺杂V_2Te_2O[47]以及K掺杂V_2Se_2O[48]等体系中观察到显著的自旋能带劈裂. 上述研究结果更加佐证了交错磁体材料的广泛存在.

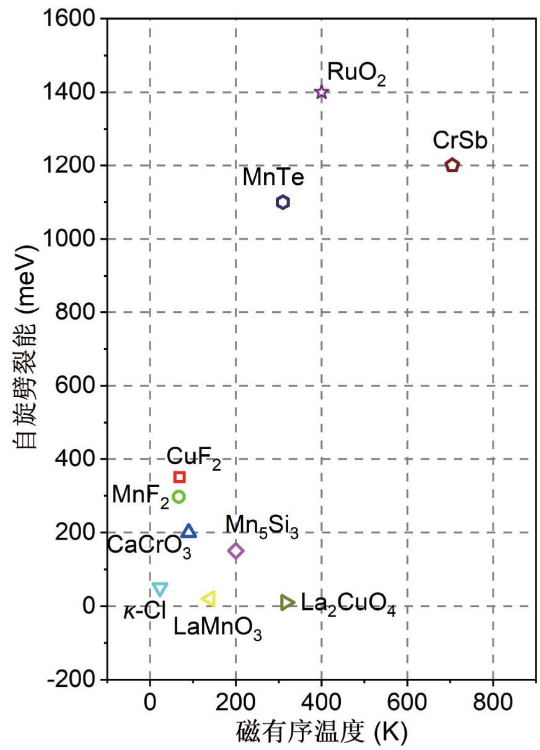

图 2 (网络版彩图)典型的交错磁体材料: 横坐标为磁有序温度，纵坐标为自旋劈裂能[2]

Figure 2 (Color online) Typical altermagnets: the horizontal axis is the magnetic ordering temperature, and the vertical axis is the spin splitting energy [2].

值得注意的是，尽管交错磁体这一概念本身已得到广泛支持，但在对部分材料交错磁性的表征上仍需要足够的谨慎. 例如，前期研究广泛确定了RuO_2具有反铁磁序[49,50]，但近期也有实验表明上述体系中缺乏长程磁序[51–53]. 此外，ARPES观测证实了RuO_2动量空

间中的能带自旋劈裂[26,54], 近期也有研究论文给出不同结论[55]. 这些不一致或源于RuO_2磁性对化学计量比[56]或应力[57,58]的高度敏感特性, 不同研究组的样品可能表现出有差异性的结果. 有意思的是, 很多研究组的样品普遍观察到RuO_2/铁磁金属异质结存在交换偏置, 这一经典而又宏观的效应很好地说明了RuO_2中存在反铁磁序. 最近通过奈尔自旋轨道矩效应使RuO_2的奈尔矢量翻转90°, 相对应的X射线磁线二色谱的极性反号等实验强有力地确定了能观察到自旋劈裂效应的RuO_2样品中存在反铁磁序[59,60]. 研究发现, 在交错磁体MnTe中, 微量Mn成分富集会诱导出微弱铁磁性[61], 其对MnTe的交错磁性的影响仍需进一步澄清[62,63]. 上述样品相关性表明交错磁性的研究还有广阔的空间, 需要更精确、更系统的实验表征和深入分析.

4　交错磁体的研究现状

4.1　交错磁体中自旋劈裂相关的输运行为

磁性材料中自旋与电荷的相互作用及其输运行为是自旋电子学的核心研究内容之一. 在交错磁体中, 自旋劈裂的能带结构会带来一系列时间反演对称破缺的非平庸磁输运响应, 包括反常霍尔效应(Anomalous Hall Effect, AHE)[29–33,64–72]、非线性输运行为[73,74]、反常能斯特效应(Anomalous Nernst Effect, ANE)[75,76]、磁光克尔效应(Magneto-Optical Kerr Effect, MOKE)[31,77–80]、巨磁阻(Giant Magnetoresistance, GMR)/隧穿磁电阻(Tunneling Magnetoresistance, TMR)效应[7,8,81–86]以及自旋-电荷双向转化[10,15,87–96]等. 在本节中, 根据是否依赖自旋-轨道耦合(Spin-Orbit Coupling, SOC), 上述效应可分为两类: 一类是AHE, ANE以及MOKE等, 需要SOC, 这一类效应丰富了交错磁体的性能; 另一类如自旋-电荷双向转化和TMR, 无需SOC, 这一类效应才是交错磁体的指纹特征. 以下将分别总结这些效应的最新实验进展.

(1) 反常霍尔效应、磁光克尔效应与反常能斯特效应

AHE来源于非零的贝里曲率. 当考虑自旋轨道耦合后, 交错磁体的自旋劈裂能带的交叉点处将打开小间隙, 贡献巨大的贝里曲率[30], 从而产生常规反铁磁中所观测不到的AHE[29–33,64–72] (图3(a)). 然而, 铁磁材料与交错磁体的AHE的表现形式存在显著差异: 首先, 铁磁材料中自旋劈裂由宏观磁化引起, 无论磁矩方向如何, 对称性均允许AHE存在; 而在交错磁体中, 自旋劈裂来源于非磁原子的各向异性晶体场, 因此AHE的存在与否受奈尔矢量方向调制, 奈尔矢量排列的不同方向会改变AHE的对称性[6,66,71]; 此外, 不同于铁磁材料中取决于宏观磁矩的AHE, 交错磁体的AHE取决于奈尔矢量, 奈尔矢量的180°翻转将带来AHE极性的反转[31]. 值得注意的是, 并非所有的交错磁体均具有AHE, 当且仅当交错磁体材料的磁点群属于31种铁磁点群时, 材料体系的对称性才允许一阶AHE的存在[17]. 此外, 对于部分交错磁体材料, 尽管其磁点群不允许一阶AHE的存在, 但其磁对称性仍允许高阶AHE的存在[17]. 例如, 在交错磁体RuO_2[73], VNb_3S_6[74]等材料体系中, 非零的贝里曲率四极子和量子几何四极子会分别带来横向的高阶AHE与纵向的非线性输运行为. 在这里, 我们所讨论的AHE仅指一阶线性的AHE.

交错磁体中的AHE广泛存在于金属以及半导体等多种物相中, 目前已在RuO_2[64], α-MnTe[65], Mn_5Si_3[30,31]和CrSb[72]中观测到显著的AHE. 对于绝缘交错磁体, AHE无法直接观测, MOKE成为探测磁矩排列的重要手段, 是AHE的“高频响应”[77–80](图3(b)). 实验上, MOKE信号已在Mn_5Si_3薄膜[31]和κ-Cl[10]中被观测到, 并与奈尔矢量排列相关. 此外, 研究人员结合时间分辨技术, 通过α-MnTe中的TR-MOKE成功探测其磁动力学行为[80].

ANE因其横向热电转化特性, 在大规模废热利用和器件结构优化中具有重要潜力(图3(c)). 与AHE类似, ANE的存在依赖于时空对称性的破缺以确保贝里曲率非零, 不同的是, AHE的内禀机制来源于贝里曲率在占据态能带的积分; 而ANE的内禀机制则敏感于费米面附近能带贝里曲率的积分[97]. 实验上, ANE已在交错磁体Mn_5Si_3中被观测到[75,76], 如图3(c)所示, 在正负外磁场的作用下, Mn_5Si_3的奈尔矢量发生180°翻转, 从而带来贝里曲率以及对应ANE信号的反转[31], 这一现象为交错磁体在热电能量转化中的应用提供了重要支持.

(2) 自旋-电荷双向转化

在交错磁体中, 携带相反自旋的磁性原子周围的非磁原子的交错排列导致了各项异性的能带劈裂. 当在材料中通入电流时, 交错劈裂的费米面在电场作用下发生移动, 随电流与晶体取向的不同, 可以分别产

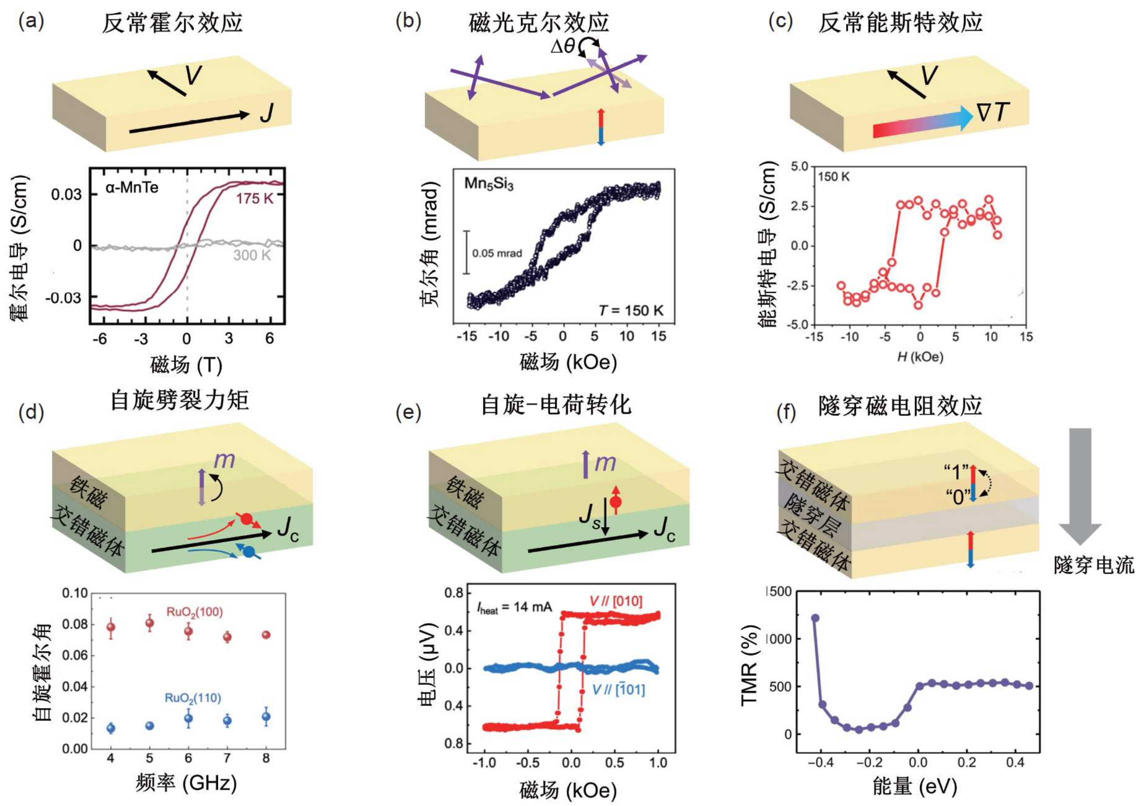

图 3 (网络版彩图)交错磁体中自旋劈裂相关的输运行为. (a) 交错磁体反常霍尔效应示意图以及α-MnTe的AHE曲线, 在奈尔温度以下(175 K, 红线)观测到反常霍尔电导随磁场变化, 而在奈尔温度以上(300 K, 灰线)反常霍尔电导为0. 图片取自文献[65], 已获授权. Copyright©2023, American Physical Society. (b) 交错磁体中磁光克尔效应示意图以及交错磁体Mn_5Si_3克尔信号随外磁场的变化曲线. 图片引用遵循CC 4.0 BY-SA版权协议[31]. Copyright©2024, the Authors, Published by American Association for the Advancement of Science. (c) 交错磁体反常能斯特效应示意图以及Mn_5Si_3在外磁场操控下反常能斯特电压的变化曲线[75]. (d) 交错磁体中自旋劈裂力矩示意图以及利用ST-FMR表征不同取向RuO_2的自旋霍尔角大小. 图片取自文献[89], 已获授权. Copyright©2022, American Physical Society. (e) 交错磁体中自旋-电荷转化示意图以及利用Co/Pt向RuO_2注入自旋的实验结果, 利用面外磁场操控Co/Pt磁矩方向, 从而改变面外注入自旋的极化方向以及RuO_2中的纵向电压. 图片取自文献[92], 已获授权. Copyright©2023, American Physical Society. (f) 利用交错磁体构筑的隧道结示意图以及理论计算RuO_2(100)/TiO_2(001)/RuO_2(001)三层膜体系的TMR值. 图片引用遵循CC 4.0 BY-SA 版权协议[7]. Copyright©2021, the Authors, Published by Springer Nature

Figure 3 (Color online) Transport behaviors related to spin splitting in altermagnets. (a) Schematic diagram of the anomalous Hall effect in altermagnets and the AHE curve of α-MnTe [65]. Below the Néel temperature (175 K, red line), the anomalous Hall conductance is observed to vary with the magnetic field, while above the Néel temperature (300 K, gray line), the anomalous Hall conductance is zero. Reprinted with permission from ref. [65]. Copyright©2023, American Physical Society. (b) Schematic diagram of the magneto-optical Kerr effect in altermagnets and the curve of the Kerr signal of altermagnet Mn_5Si_3 varying with the external magnetic field [31]. Reproduced under the terms of the CC-BY 4.0 license [31]. Copyright©2024, the Authors, Published by American Association for the Advancement of Science. (c) Schematic diagram of the anomalous Nernst effect in altermagnets and the curve of the anomalous Nernst voltage of Mn_5Si_3 under the control of the external magnetic field [75]. (d) Schematic diagram of the spin-splitting torque in altermagnets and the use of ST-FMR to characterize the spin Hall angle of RuO_2 with different orientations. Reprinted with permission from ref. [89]. Copyright©2022, American Physical Society. (e) Schematic diagram of spin-charge conversion in altermagnets and experimental results of injecting spin into RuO_2 using Co/Pt. Here, the direction of the Co/Pt magnetic moment is manipulated by an out-of-plane magnetic field, thereby changing the polarization direction of the out-of-plane injected spin and the longitudinal voltage in RuO_2. Reprinted with permission from ref. [92]. Copyright©2023, American Physical Society. (f) Schematic diagram of the tunnel junction constructed using altermagnets and theoretically calculated TMR value of the RuO_2(100)/TiO_2(001)/RuO_2(001) trilayers. Reproduced under the terms of the CC 4.0 BY-SA license [7]. Copyright©2021, the Authors, Published by Springer Nature.

生自旋极化电流和纯自旋流, 而自旋极化方向始终与奈尔矢量方向保持一致[15,87–91] (图3(d)). 该效应被称为自旋劈裂力矩(Spin-Splitting Torque, SST)[89], 其与自旋-轨道力矩(Spin-Orbit Torque, SOT)[98]具有本质区别: 前者不需要SOC的存在, 而后者需要. 在实验方面, 研究人员一方面通过自旋力矩铁磁共振(Spin-Torque

Ferromagnetic Resonance, ST-FMR)[88–91,95]和谐波分析等手段, 表征了d波劈裂交错磁体RuO_2中SST的自旋极化方向、自旋流动方向与电荷-自旋转化效率. 此外, 利用RuO_2中SST产生的面外自旋, 实现了垂直磁化铁磁层的无辅助场翻转[99–101].

SST可实现电荷到自旋的转化, 其逆过程同样可在交错磁体中实现, 即向交错磁体注入自旋流时, 费米面发生移动从而产生电荷流(图3(e)). 实验上, 一方面研究人员借助电学输运手段, 如自旋泵浦(Spin Pumping)[91,96]以及自旋塞贝克效应(Spin Seebeck Effect, SSE)[92,96], 向RuO_2中注入自旋, 通过电压探测表征了自旋-电荷逆转化过程; 另一方面, 借助光学手段(太赫兹泵浦光)向交错磁体中注入自旋[93], 观测对应的太赫兹发射谱, 从而实现了交错磁体中自旋-电荷转化的光学探测.

(3) 隧穿磁电阻效应

交错磁体的能带自旋劈裂带来特定方向上显著的自旋极化. 当构建交错磁体/绝缘层/交错磁体的三层结构时, 理论上可产生显著的TMR效应[7,8] (图3(f)). 从能带角度看, 奈尔矢量的180°翻转会导致自旋劈裂的反转, 从而改变导电通道的电导率和隧穿透过率, 带来磁电阻的变化[7,8,81–84]. Shao等人[7,82]探索了不同材料体系的TMR效应, 并阐述了交错磁体中TMR的两类物理图像. 以RuO_2为例, 当电流垂直于(001)面注入时, 自旋向上和向下的导电通道数目相同, 总体呈自旋中性. 然而, 隧道结中上下两层交错磁体奈尔矢量的相对取向会改变导电通道的匹配程度, 由此可以在RuO_2(001)/TiO_2(001)/RuO_2(001)三层膜结构中得到高达500%的TMR值[7]. 而当电流垂直于(110)面注入时, 自旋向上和向下的导电通道数目不同, 会产生自旋极化电流, 根据Julliere模型实现TMR效应[82]. 此外, 绝缘交错磁体本身也可作为隧穿层, 在金属交错磁体/绝缘交错磁体/非磁金属或金属铁磁体/绝缘交错磁体/非磁金属的三层膜体系中, 导电通道的匹配与否同样会产生显著的TMR值[85,86]. 尽管诸多理论工作已经在多种交错磁体材料体系中预测了隧穿磁电阻效应, 但实验研究尚不充分, 交错磁体隧道结的实验验证仍有待未来深入探索.

4.2 交错磁体中自旋劈裂的调控

实现对交错磁体自旋劈裂的调控是构筑高性能自旋电子学器件的关键前提. 在铁磁材料中, 自旋转移力矩(Spin Transfer Torque, STT)和SOT[98]已被广泛用于磁矩的电学翻转; 而在反铁磁体系中, SOT被用于实现奈尔矢量的翻转, 如在共线反铁磁体系CuMnAs[102], Mn_2Au[103], NiO[104], α-Fe_2O_3[105]等体系中实现了奈尔矢量的90°或120°翻转, 在非共线反铁磁Mn_3Sn等体系中实现了磁八极子的60°或180°翻转[106,107].

对于共线的交错磁体体系, 实现奈尔矢量的180°翻转能够改变自旋劈裂的极性, 从而调控器件性能, 对于构筑基于交错磁体的实用化电控器件具有重要意义(图4(a)). 然而, 由于其奈尔矢量180°翻转前后的两个状态在能量上完全简并, 通常无法实现确定性的翻转(图4(a)). 在部分交错磁体, 例如Mn_5Si_3中, 对称性允许材料体系中存在奈尔矢量倾转所导致的微弱剩磁, 通过施加外磁场作用于上述剩磁, 可以人为构造翻转前后状态之间的非对称势垒(图4(a)). 在非对称势垒的情况下, SOT可以驱动奈尔矢量发生确定性180°翻转, 翻转的结果可通过横向的反常霍尔电压进行读出(图4(b))[31]. 值得注意的是, 在SOT翻转Mn_5Si_3奈尔矢量的过程中, 电流热效应扮演着重要作用: Mn_5Si_3的电学翻转可在奈尔温度以下和以上分别发生, 这两种情形具有截然不同的翻转行为, 表现为热效应对于电学翻转的显著调制[108] (图4(c)).

交错磁体中的自旋劈裂来源于其独特的磁空间群对称性, 而磁空间群的改变会对自旋劈裂能带产生显著影响. 例如, 在CrSb块体中, 尽管存在自旋劈裂, 磁空间群对称性不允许AHE的出现. 然而, 在薄膜状态下, 基片应力引起的晶格畸变降低了磁空间群对称性, 从而在薄膜CrSb中观察到AHE的存在[72]. 类似的, 在Mn_5Si_3块体中, tT对称性使得净剩贝里曲率为零. 而在薄膜状态下, 通过基片施加应力可以破缺上述tT对称性, 诱导自旋劈裂并引发AHE[29–31]. 更为重要的是, 磁空间群的调控可以实现对CrSb中奈尔矢量180°翻转模式的调控, 在此基础上设计出能无场100%高效翻转的自旋力矩器件[72].

5 交错磁体研究未来展望

交错磁体兼具铁磁与反铁磁材料的诸多特点, 带来一系列全新的物理现象以及广阔的器件应用前景. 以下简要展望交错磁体未来的研究方向, 包括新型自

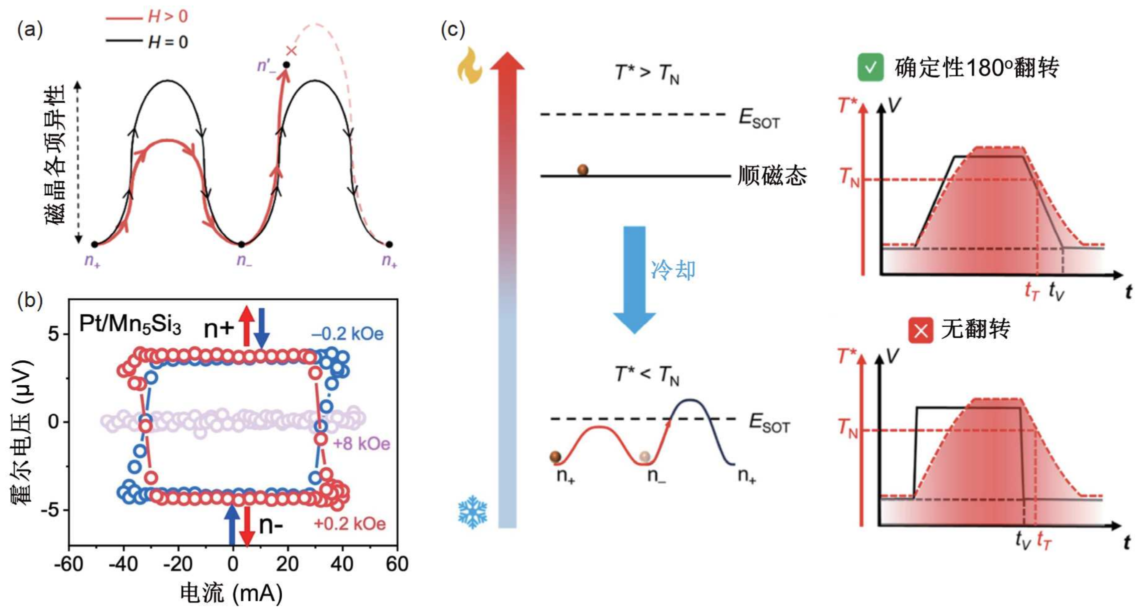

图 4　(网络版彩图)交错磁体自旋劈裂的电学操控. (a) 利用辅助磁场构造Mn_5Si_3翻转非对称势垒示意图, 其中$\mathbf{n}_+$与$\mathbf{n}_-$表示Mn_5Si_3奈尔矢量180°翻转前后的两个状态. 图片引用遵循CC 4.0 BY-SA版权协议[31]. Copyright©2024, the Authors, Published by American Association for the Advancement of Science. (b) 不同辅助磁场下, Mn_5Si_3的霍尔电压与翻转电流关系曲线. 图片引用遵循CC 4.0 BY-SA版权协议[31]. Copyright©2024, the Authors, Published by American Association for the Advancement of Science. (c) Mn_5Si_3电学操控过程中热效应与SOT耦合机制示意, 其中, 对于翻转过程中器件温度超过奈尔温度的情形, 长脉冲下降沿的写入脉冲会带来确定性的翻转结果, 而短脉冲下降沿的写入脉冲则不会造成确定性翻转. 图片取自文献[108], 已获授权. Copyright©2024, American Physical Society

Figure 4 (Color online) Electrical manipulation of spin splitting in altermagnets. (a) Schematic diagram of the construction of the asymmetric energy barrier for Mn_5Si_3 switching using an assistant magnetic field, where $\mathbf{n}_+$ and $\mathbf{n}_-$ represent the two states before and after the 180° switching of the Mn_5Si_3 Néel vector. Reproduced under the terms of the CC 4.0 BY-SA license [31]. Copyright©2024, the Authors, Published by American Association for the Advancement of Science. (b) Curves of the relationship between the Hall voltage and switching current of Mn_5Si_3 under different assistant magnetic fields. Reproduced under the terms of the CC 4.0 BY-SA license [31]. Copyright©2024, the Authors, Published by American Association for the Advancement of Science. (c) Schematic diagram of the coupling of thermal effects and SOT during the electrical manipulation of Mn_5Si_3. For the case where the device temperature exceeds the Néel temperature during the switching process, a writing pulse with a long pulse falling edge will bring a deterministic switching result, while a writing pulse with a short pulse falling edge will not cause deterministic switching. Reprinted with permission from ref. [108]. Copyright©2023, American Physical Society.

旋存储器件、自旋劈裂的实空间成像、交错磁体与准粒子的耦合以及交错磁体与多铁态的结合等.

交错磁体因其自旋劈裂的能带特性，可用于构建交错磁体/绝缘层/交错磁体的隧道结，理论上能够实现显著的隧穿磁电阻(TMR)效应. 将其应用于磁随机存储器(MRAM)阵列, 有望提升存储密度和抗外磁场干扰能力, 同时利用反铁磁的高本征频率优势实现更快的电学写入速度[7,8]. 然而, 由于交错磁体的自旋劈裂以及自旋流产生高度依赖于晶体学取向和奈尔矢量方向[82]，这对薄膜沉积的结晶质量和磁畴精细结构提出了严格要求. 除了MRAM, 交错磁体还可用于构建太赫兹纳米振荡器，结合反铁磁的高频特性和铁磁的大信号输出优势, 为直流驱动的太赫兹器件提供新思路[109–111].

开展对于交错磁体自旋劈裂在实空间上的成像并揭示其与材料体系输运行为的关联，对于理解交错磁体的构效关系具有重要意义. 目前，研究人员已经基于XMCD技术探测了交错磁体α-MnTe的奈尔矢量取向[112]，并结合XMLD和XMCD技术，通过光电子发射显微技术成功在α-MnTe中实现了对奈尔矢量分布的空间成像，观测到磁涡旋等复杂的拓扑磁畴结构[113]. 进一步观测交错磁体磁畴结构对电流、电压、应力等外部激励的响应，对于构筑基于交错磁体的电控存储器、赛道存储器等新型器件具有重要意义. 除此之外，交错磁体中也存在丰富的拓扑磁畴结构. 例如, 理论预测斯格明子霍尔角在交错磁体中会随着电流方向变化剧烈，这显著区别于常规的铁磁和共线反铁磁中的斯格明子[114]. 在空间上实现对于上述拓扑磁结构的成像, 将会给研究交错磁体带来全新视角和维度.

研究交错磁体中各类准粒子(如磁子、光子、声子等)的物理行为, 对于理解交错磁体的物理图像具有重要意义. 与电子类似, 交错磁体中两种不同手性的磁子简并性会被打破, 其色散关系曲面出现劈裂[115–118], 可能带来比传统反铁磁更为丰富的磁子输运特性. 这些特性与磁子的传播方向和交错磁体的晶体学取向高度相关, 可直接反映交错磁体的内禀自旋劈裂结构. 交错磁体与光子的相互作用同样值得关注, 由于交错磁体的本征频率可达太赫兹, 通过超快太赫兹脉冲泵浦可在匹配频段下激发并探测交错磁体的超快磁动力学行为[119–125]. 此外, 声子在交错磁体中的传输(如声表面波)会带来应变[126–128], 从而引起交错磁体的磁空间群的交变[1,2], 为自旋劈裂的物理特性调控和器件优化提供新方法. 交错磁体的多样特性为新型信息电子器件的设计和功能开发提供了丰富的可能性, 其未来研究前景令人期待.

此外, 近期的一些研究工作表明, 交错磁性还可存在于多种铁电/反铁电材料中[129,130]. 在上述体系中, 材料的交错磁性与材料的铁电序相互耦合, 通过施加外电场改变铁电极化的方向, 可以实现对于材料体系能带自旋劈裂的调控. 在实验上成功生长薄膜多铁交错磁体材料并实现对于其自旋劈裂的电场操控, 对于进一步构筑纯电压调控的低功耗高性能自旋存储器件具有重要意义.

6 总结

交错磁体结合了反铁磁无净磁矩以及铁磁材料能带自旋劈裂的特点, 已成为自旋电子学研究的热点之一. 本文首先从磁对称性的角度阐明了交错磁体区别于铁磁和常规反铁磁材料的基本特征. 随后, 围绕交错磁体中与自旋劈裂相关的输运行为及其调控, 简述了其中丰富且新奇的物理现象. 最后, 对交错磁体在基础研究与器件应用中的未来发展进行了讨论与展望. 总体而言, 交错磁体在自旋电子学器件应用与凝聚态物理前沿研究等方面具有广阔的研究前景. 然而, 针对交错磁体的研究在当下仍存在许多亟待揭示的谜团, 也反映出其作为全新研究领域的巨大潜力. 未来需要更多来自凝聚态物理、材料科学和微电子领域的研究人员共同探索, 为这一领域注入新动力.

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Research progress and future prospects of altermagnets

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As a novel magnetic phase, altermagnets exhibit staggered collinear compensated spin alignment in real space and staggered spin-splitting energy bands in reciprocal space, combining the advantages of both ferromagnets and antiferromagnets. These materials possess unique properties, such as the absence of stray fields, high intrinsic frequency, and nontrivial magnetic responses originating from time-reversal symmetry breaking. Furthermore, altermagnets span a wide range of material systems, including metals, semiconductors, insulators, and superconductors, offering profound scientific implications and versatile opportunities for exploration. This review begins by elucidating the fundamental distinctions between altermagnets and conventional ferromagnets or antiferromagnets through symmetry analysis and presenting a catalog of representative altermagnets. It then provides a comprehensive overview of recent experimental advances, with a focus on transport phenomena linked to spin splitting in altermagnets and strategies for their modulation. Lastly, this review outlines promising future research directions, such as the development of high-performance spintronic storage devices based on altermagnets, real-space imaging of spin splitting in altermagnets, the interaction of altermagnets with quasiparticles and the combination of altermagnetism with multiferroicity. These advancements and prospects highlight altermagnets as a transformative research frontier in spintronics, with immense scientific value and vast potential for practical applications.

altermagnet, altermagnetism, spin-splitting, symmetry broken, spintronics

PACS: 72.25.Ba, 72.25.Dc, 75.50.Ee, 81.05.Bx, 85.75.Dd

doi: 10.1360/SSPMA-2024-0564