Insulating and metallic p-wave magnets

1. **Electrical switching of a p-wave magnet**
   Authors: Qian Song, Srdjan Stavrić, Paolo Barone, Andrea Droghetti, Daniil S. Antonenko, Jörn W. F. Venderbos, Connor A. Occhialini, Batyr Ilyas, Emre Ergeçen, Nuh Gedik, Sang-Wook Cheong, Rafael M. Fernandes, Silvia Picozzi, and Riccardo Comin
   Nature **642**, 64–70 (2025)

2. **A metallic p-wave magnet with commensurate spin helix**
   Authors: Rinsuke Yamada, Max T. Birch, Priya R. Baral, Shun Okumura, Ryota Nakano, Shang Gao, Motohiko Ezawa, Takuya Nomoto, Jan Masell, Yuki Ishihara, Kamil K. Kolincio, Ilya Belopolski, Hajime Sagayama, Hironori Nakao, Kazuki Ohishi, Takashi Ohhara, Ryoji Kiyanagi, Taro Nakajima, Yoshinori Tokura, Taka-hisa Arima, Yukitoshi Motome, Moritz M. Hirschmann, and Max Hirschberger
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Recommended with a Commentary by Yuan Li, Institute of Physics, Chinese Academy of Sciences

Magnetism is often depicted as a pattern of ordered moments in real space: a ferromagnet (FM) has a parallel spin arrangement, whereas an antiferromagnet (AFM) arranges them in a staggered pattern with (ideally) no net moment. From a band-structure viewpoint, an FM generically breaks $\mathcal{T}$, the time-reversal symmetry, and yields spin-split bands, but it also produces stray magnetic fields. Many collinear AFMs, on the other hand, retain the combined $\mathcal{PT}$ symmetry, where $\mathcal{P}$ denotes parity. As both $\mathcal{P}$ and $\mathcal{T}$ send $\mathbf{k} \to -\mathbf{k}$, while $\mathcal{T}$ also reverses the spin, the combined $\mathcal{PT}$ operation leaves $\mathbf{k}$ unchanged but flips the spin. Therefore, when $\mathcal{PT}$ is a symmetry, the bands remain spin-degenerate even though $\mathcal{T}$ is broken in real space.

This simple contrast motivates a modern question that has become increasingly central to magneto-transport and spintronics: can one obtain spin-split electronic bands *without* a macroscopic magnetization? Clearly, the key is to break the $\mathcal{PT}$ symmetry. Meanwhile, in order for the system to produce no stray magnetic fields, it is desirable for $\mathcal{T}$ to be compensated by lattice symmetry operations that preserve the global spin-quantization axis (if there is one), such as a crystallographic rotation in the case of altermagnets [1].

The term "p-wave magnet" originally appeared in a momentum-space setting: Hirsch proposed a spin-channel $l = 1$ ("p-wave") Pomeranchuk instability in which the spin-up and spin-down Fermi surfaces undergo opposite *zero-total-momentum* distortions (or relative shifts), generating a parity-breaking yet $\mathcal{T}$-preserving spin-split state [2]. In contrast, the more recent proposal [3] adopted in the present context builds on a translational-symmetry-breaking scheme in real space: the magnetic ground state forms a coplanar but non-collinear spin helix at a finite propagation vector $\mathbf{Q}$, such that $\mathcal{T}$ can be "restored" only when combined with a lattice translation. The magnetic order not only breaks parity but also "folds" the Brillouin zone (when commensurate with the original lattice; Fig. 2) along the propagation vector, as believed to be the case in CeNiAsO [3]. In this case, the order features a single propagation vector within a plane that would otherwise have four-fold rotational symmetry, thereby breaking the in-plane C_4 symmetry. As a result, a large spontaneous anisotropy of in-plane resistivity was proposed as one possible signature of p-wave magnetism. This anisotropy has recently been observed experimentally [4].

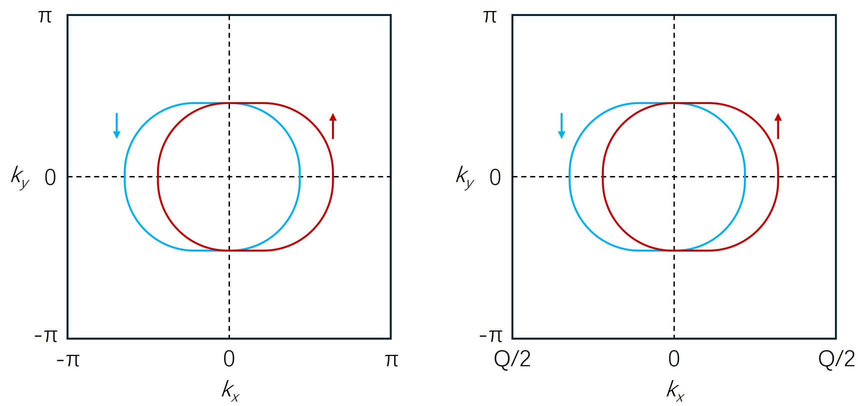

Figure 1: Spin-spit Fermi surfaces of a p-wave magnet as realized from a spin Pomeranchuk instability (left) and magnetic order with a finite propagation vector (right).

A distinctive characteristic of p-wave magnets is that the spin quantization axis in momentum space is perpendicular to the spin plane in real space ($\mathbf{n}$ denotes the plane's normal direction). One can intuitively understand this by following an itinerant electron that travels through the magnetic lattice: as the electron visits adjacent lattice sites along the propagation vector ($\mathbf{Q}$) of the magnetic order, it sees local spins rotating about $\mathbf{n}$. This forces its own spin to rotate as well, which mimics spin precession in a fictitious magnetic field, $\mathbf{H} \parallel \mathbf{n}$. The fictitious field polarizes the itinerant electron, and the sign of the polarization depends on the direction of motion.

In the first paper, Song *et al.* report a comprehensive set of observations of a parity-breaking magnetic order in a van der Waals magnet, NiI_2. The cycloidal magnetic order, with $\mathbf{n} \perp \mathbf{Q}$, is a prototypical type-II multiferroic [5]. Together with the material's insulating nature, this enables electric-field control of magnetic domains in small samples, and their detection via photocurrent measurements along the $\mathbf{Q} \times \mathbf{n}$ direction. In a separate experiment, the coupling between electron momentum ($\mathbf{k} \parallel \mathbf{Q}$) and spin ($\mathbf{S} \parallel \mathbf{n}$) allows observation of the circular photogalvanic effect (CPGE) in a single magnetic domain: illumination with circularly polarized light injects spin polarization into the sample and unequally pumps electrons at $\pm\mathbf{k}$, generating a charge current in the direction of $\mathbf{Q}$. The CPGE provides direct evidence of odd-parity spin polarization in the material.

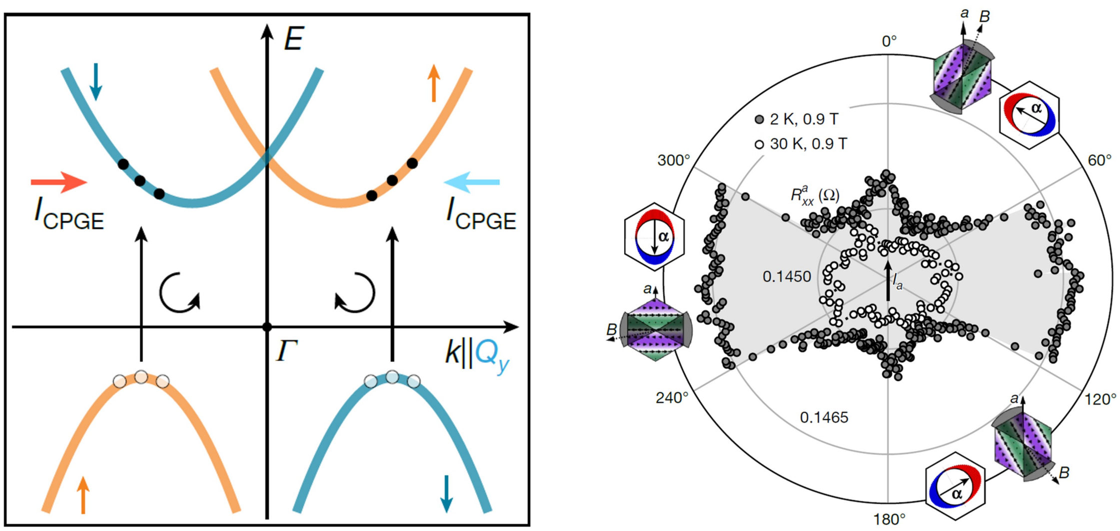

Figure 2: Figures adapted from Song *et al.* and Yamada *et al.* with CPGE (left) and in-plane field-controlled resistivity anisotropy (right) as signatures of the p-wave magnetic state in NiI_2 and $Gd_3(Ru_{1-\delta}Rh_\delta)_4Al_{12}$, respectively.

In the second paper, Yamada *et al.* report the realization of a p-wave magnetic ground state in a metallic compound, $Gd_3(Ru_{1-\delta}Rh_\delta)_4Al_{12}$. The authors fabricate their crystal into a delicate strain-free device and demonstrate the development of an in-plane resistivity anisotropy in the magnetically ordered state, the direction of which can be further controlled by external magnetic fields. The magnetic propagation vector and the spin plane are further determined by resonant X-ray diffraction experiments, establishing $\mathbf{n} \parallel \mathbf{Q}$. The spin arrangement corresponds to a proper screw [5], which does not produce ferroelectric polarization despite the broken parity. While this does not allow the magnetic domains to be uniquely prepared as in NiI_2, a remarkable aspect is that the Rh doping δ is carefully tuned to $\delta \approx 0.05$, such that the RKKY interactions stabilize magnetic order with a period that is evenly commensurate with the crystal lattice ($N = 6$). This is arguably crucial for a "pure" p-wave magnet: odd-commensurate order does not genuinely preserve $\mathcal{T}$ symmetry (up to a lattice translation), whereas incommensurate order would break lattice translational invariance and lose a rigorous momentum-space description.

Both materials share the same essence in the spin point-group definition of p-wave magnets, *i.e.*, with broken $\mathcal{P}$ and preserved $C_{2\mathbf{n}}\mathcal{T}$ symmetry ($C_{2\mathbf{n}}$ is a 180° spin-only rotation about $\mathbf{n}$). Each of the two cases has certain advantages, as well as trade-offs: In the case of NiI_2, while the insulating multiferroic nature allows for magnetic domain manipulation by electric fields, the use of spin-split bands in transport devices might be relatively limited. Moreover, as the propagation vector is controlled by the relative strengths of exchange interactions, it is likely to be incommensurate in general. By contrast, commensurate order is more feasible in metallic systems, thanks to the tunable Fermi level. However, the coupling between localized and itinerant electrons also introduces a tendency to "snap" the propagation vector to a commensurate value when the Fermi surface nesting condition is not far off, at the cost of inducing weak ferromagnetism [6]. The net moment is expected to point in the plane of the spin helix, *i.e.*, perpendicular to the odd-parity spin polarization, thereby introducing a departure from the ideal p-wave magnetism. This effect is likely responsible for the observed anomalous Hall effect in $Gd_3(Ru_{1-\delta}Rh_\delta)_4Al_{12}$ reported in the second paper. In other words, unless the nesting wave vector can be precisely tuned to a commensurate value, weak ferromagnetism appears to be unavoidable in RKKY-mediated p-wave magnets.

Would it be possible to combine the strengths of both types, and realize an evenly commensurate cycloidal magnetic order in a metallic system with electric-field-controllable domains? The answer is not obvious at present. Transition-metal compounds in which Heisenberg exchange interactions dominate over RKKY interactions might be a good starting point. Indeed, the original candidate CeNiAsO appears to meet this expectation, but details of its magnetic ground state and interactions still await further study.

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