lines with a smaller width are not sufficient to support adhesion. It was evident that only in the presence of two-dimensional ligand geometries created by parallel or crossing lines were adhesion clusters assembled and stabilized on cells even for ≤30-nm fibres. Considering the size of $\alpha_v\beta_3$ integrins[8], on the thinner fibres only single integrins could be accommodated in single file. This suggests that the lateral interactions of receptors are crucial for the maintenance of stable adhesions.

The ligand binding region in β_3 integrins is essential for the maintenance of receptor function and clustering. This is lost in D119Y mutation of the ectodomain, which makes the receptor no longer able to bind to its ligand, whereas N305T mutation renders the receptor constitutively active[9]. Expression of the D119Y mutated integrins in addition to the endogenous β_3 integrins in cells reveals that the inactive receptors intercalate with the endogenous active receptors. The identification of the function of these unliganded receptors in building bridges between nanoclusters of bound integrins is the main finding of this work. In particular, the bridging of parallel lines presenting the RGD ligands due to the activation of unliganded integrins is required for adhesion stability. Interestingly, dense integrin clusters formed on substrates with parallel (within 100 nm) or crossing thin lines; these clusters resemble those formed on cells adhering to a continuous ligand coated substrate.

The researchers propose that the recruitment of talin, a focal adhesion protein that directly links integrins to actin, might prevent the pulling of unliganded integrins from the actomyosin machinery. It is possible that talin would localize in the bridged clusters, since the separation of bound integrins still offers enough space to allow its elongated configuration and its scaffold function[10]. In this respect, geometry might not always be favourable for stability, as shown from the results on single lines.

This study demonstrates that single thin fibres are unable to support adhesion of cells even with sufficient ligand density; rather, they support transient adhesion events. Instead, adhesion is better supported when fibres are in parallel, are crossing or are wide enough, highlighting the significance of matrix geometry. Moreover, the role of adhesion proteins such as focal adhesion kinases, talins and integrins in the context of cell adhesion are also highlighted in this study. This work will stimulate further research in the field of material science and mechanobiology, and further work should serve to determine how different integrin subtypes might localize within the clusters depending on fibre geometries, whether these geometries favour crosstalk with other receptors such as receptor tyrosine kinases in the assembly of adhesions, as well as with matrix metalloproteinases in the remodelling of the matrix. ❐

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References

1. Changede, R., Xu, X., Margadant, F. & Sheetz, M. P. *Dev. Cell* **35**, 614–621 (2015).
2. Geiger, B. & Yamada, K. M. *Cold Spring Harb. Perspect. Biol.* **3**, a005033 (2011).
3. Schvartzman, M. et al. *Nano Lett.* **11**, 1306–1312 (2011).
4. Cavalcanti-Adam, E. A. et al. *Biophys. J.* **92**, 2964–2974 (2007).
5. Arnold, M. et al. *Soft Matter* **5**, 72–77 (2009).
6. Oria, R. et al. *Nature* **552**, 219–224 (2017).
7. Changede, R. Cai, H., Wind, S. J. & Sheetz, M. P. *Nat. Mater.* https://doi.org/10.1038/s41563-019-0460-y (2019).
8. Xiong, J. P. et al. *Science* **296**, 151–155 (2002).
9. Cluzel, C. et al. *J. Cell Biol.* **171**, 383–392 (2005).
10. Golji, J. & Mofrad, M. R. K. *Biophys. J.* **107**, 1802–1809 (2014).

2D MAGNETS

Van der Waals engineering of magnetism

Pressure-induced changes in the layer stacking order is found to result in new magnetic ground states in two-dimensional insulating CrI_3. Such van der Waals engineering should provide ample opportunities to design desired magnetic phases.

Ji-Hui Yang and Hongjun Xiang

For decades, we have tried to functionalize magnetism, the heart of which lies in controlling magnetic orders. With the discovery of two-dimensional (2D) magnetic materials[1,2], atomically thin magnets provide us with a new platform to manipulate magnetic states with the dream of realizing integrable and wearable magnetic devices. So far, various strategies such as electrostatic gating[3] and isovalent alloying[4] have been proposed to control magnetism in 2D magnets. Now, writing in *Nature Materials*, two groups, Tingxin Li and colleagues[5] as well as Tiancheng Song and colleagues[6], independently demonstrate a new approach to manipulate magnetic states, using van der Waals (vdW) engineering to tune the magnetic order in 2D magnets. VdW engineering is becoming a popular technique to manipulate physical properties of 2D multilayer materials. By changing stacking orders, sequences or patterns in 2D materials, interlayer interactions can be tuned to induce new physical phases, phenomena and properties. For example, stacking two graphene monolayers with certain twist angles leads to an interesting superconducting phase[7]. Li et al. and Song et al. adapted vdW engineering for the first time to the 2D magnet CrI_3, and demonstrated that vdW engineering via hydrostatic pressure can modify the stacking order in CrI_3, thus inducing an irreversible interlayer antiferromagnetic (AFM) to ferromagnetic (FM) transition.

Bulk CrI_3 has two phases depending on the layer stacking orders, a monoclinic stacking phase (Fig. 1a) at room temperature and a rhombohedral phase (Fig. 1b) at low temperature. The latter phase displays FM interlayer coupling below the critical temperature of 61 K. However, when CrI_3 is exfoliated into thin films, the adjacent monolayers are antiferromagnetically coupled — that is, bilayer CrI_3 is an antiferromagnet (Fig. 1a). The origin of interlayer AFM coupling in CrI_3 exfoliated thin films has remained a puzzle for a quite a while, although it has been theoretically suggested that stacking order may play a role[8,9].

To solve the above puzzle, a critical issue is to manipulate the stacking order

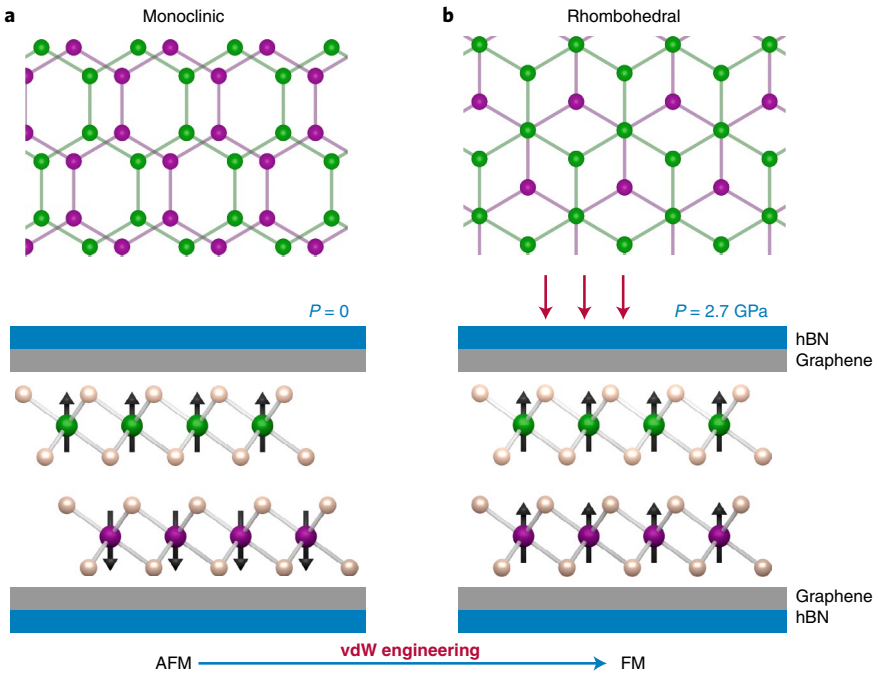

Fig. 1 | Van der Waals engineering of magnetic ordering in bilayer CrI3. a, Top and side view of monoclinic stacking with the antiferromagnetic interlayer coupling under zero pressure *P*. The green (purple) atoms represent the Cr atoms in the top (bottom) layer, and the brown ones represent the I atoms. Black arrows represent the spin direction. **b**, Same for rhombohedral stacking with the ferromagnetic interlayer coupling under a certain pressure, represented by the red arrows. hBN, hexagonal boron nitride. Adapted from ref. [6], Springer Nature Ltd.

and magnetism of CrI_3 thin films. Li et al. and Song et al. adopted the clever idea of using hydrostatic pressure to engineer the layer separation and stacking order. In their studies, CrI_3 thin films were sandwiched by few-layer graphene contacts to form a magnetic tunnel junction (MTJ) and the MTJ device was encapsulated with hexagonal boron nitride to protect CrI_3 from the environment (Fig. 1). Hydrostatic pressure was then applied to the entire device to control the interlayer coupling via the interlayer spacing. By measuring the tunnelling current or conductance versus magnetic field, the authors were able to detect the spin-flip transition and thus determine the magnetic transition. After releasing pressure, magnetic circular dichroism measurements were performed to further probe sample magnetizations.

Before applying pressure, both groups demonstrated AFM interlayer coupling in bilayer CrI_3 with a critical magnetic field of 0.6–0.75 T to realize spin-flip transitions. As pressure was increased up to about 2.0 GPa, Song et al. found that the critical field for the spin-flip transition was almost doubled compared to the zero-pressure value, indicating a strengthening of the AFM interlayer coupling. However, when the pressure was further increased to 2.7 GPa, they found that the bilayer CrI_3 switched from an interlayer AFM state to an interlayer FM state. Li et al. found similar AFM to FM phase transition in bilayer CrI_3 on increasing pressure.

To correlate the pressure-induced interlayer AFM to FM transition with crystal structure, both groups performed Raman spectroscopy measurements. Before applying pressure, the stacking is monoclinic, consistent with a recent second harmonic study[10]. After applying pressure, a monoclinic to rhombohedral structural transition accompanies the interlayer AFM to FM transition. Such a structural transition is irreversible after removing pressure. This is consistent with previous first-principles calculations, which showed that the monoclinic AFM state of bilayer CrI_3 is less stable than the rhombohedral FM state at zero temperature[8,9]. Similar AFM to FM transition was observed in thicker CrI_3 thin films. Due to the inhomogeneous pressure-induced effect, multiple magnetic phases with mixed magnetic domains can coexist in CrI_3 thin films. Song et al. found three distinct magnetic phases in trilayer CrI_3 after removing pressure.

Several research directions related to the studies of Li et al. and Song et al. deserve further exploration. First, the exact stacking structures of CrI_3 thin films need to be identified by atomically resolved imaging to directly examine the correlation between stacking order and magnetism. Second, why all as-grown CrI_3 thin-films adopt the monoclinic stacking is not fully understood. It may be due to extrinsic effects such as capping layers and/or substrates effects, or intrinsic effects such as a lower monoclinic to rhombohedral phase transition temperature in 2D thin films. Third, is it possible to manipulate the magnetic order by controlling the stacking order with electric field since stacking order has been shown to relate to ferroelectric polarization[11]? Last but not least, there are vast opportunities for using vdW engineering techniques (pressure, twist and so on) to design desirable physical properties (magnetic, optical, thermal, electric and so on).

The studies of Li et al. and Song et al. applied vdW engineering to 2D magnets and demonstrated hydrostatic pressure as an effective approach to manipulate stacking orders of 2D magnetic materials. Their studies not only solve the puzzle of the interlayer AFM coupling in exfoliated CrI_3 thin films, but also promise a way to realize unprecedented magnetic phases by vdW engineering — for example, in moiré superlattices of twisted magnetic bilayers. ❐

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References

1. Huang, B. et al. *Nature* **546**, 270–273 (2017).
2. Gong, C. et al. *Nature* **546**, 265–269 (2017).
3. Jiang, S., Shan, J. & Mak, K. F. *Nat. Mater.* **17**, 406–410 (2018).
4. Huang, C. et al. *J. Am. Chem. Soc.* **140**, 11519–11525 (2018).
5. Li, T. et al. *Nat. Mater.* https://doi.org/10.1038/s41563-019-0506-1 (2019).
6. Song, T. et al. *Nat. Mater.* https://doi.org/10.1038/s41563-019-0505-2 (2019).
7. Cao, Y. et al. *Nature* **556**, 43–50 (2018).
8. Jiang, P. et al. *Phys. Rev. B* **99**, 144401 (2019).
9. Sivadas, N. et al. *Nano Lett.* **18**, 7658–7664 (2018).
10. Sun, Z. et al. *Nature* **572**, 497–501 (2019).
11. Fei, Z. et al. *Nature* **560**, 336–339 (2018).