dispersive waves — which can mediate the formation of robust bound states[9]: soliton pairs trapped at specific separations. Bao and colleagues also experimented with such co-rotating bound states, and demonstrated the strength of the interactions to translate into substantial quenching of the solitons' relative jitter. Indeed, the authors measured a relative root-mean-square jitter of just 600 attoseconds (integrated from 1 Hz to 2 MHz) — more than two orders of magnitude lower than the quantum limit.

The ability to resolve quantum-limited fluctuations of soliton microcombs is a landmark result, but it is important to emphasize that the measurements of Bao and colleagues revolve around the relative jitter between two solitons. In contrast, two other studies have emerged more recently that directly probe the absolute (rather than relative) jitter with sensitivity breaking the quantum limit. Reporting in *Optica*, Dongin Jeong and colleagues used a fibre delay-line-based self-heterodyne method to characterize the jitter of a 22 GHz soliton microbomb generated in a silica wedge resonator, and found the jitter power spectral density to approach the theoretically predicted quantum limit in the 300 kHz–1 MHz range[10]. In another study appearing in *Physical Review Letters*, Kunpeng Jia and colleagues leveraged stimulated Brillouin scattering in a monolithic fibre resonator to realize a soliton comb with unprecedented phase noise, reaching the quantum level for offset frequencies above 10 kHz (ref. [11]).

A central conclusion that arises from all three of the recent studies[1,10,11] is that the analytical formula derived for quantum-limited jitter of soliton microcombs appears to be spot on. It is very satisfying to see a complex theoretical formula that emerges as a tour de force analysis of soliton jitter[7] be so unequivocally confirmed by three near-simultaneous experiments. And with its validity established, the formula may now be comfortably used to identify experimental parameters that minimize quantum-limited jitter.

Bao and colleagues close their work by pointing out that resonators with low nonlinearity and low finesse would seem best suited for minimizing quantum jitter[1]. Interestingly, these characteristics point towards the macroscopic sibling of monolithic microresonators — the optical fibre ring resonator. Of course, such fibre resonators are more susceptible to environmental technical noise compared with their integrated microresonator counterparts, and they require considerably higher pumping power to operate. Nonetheless, it is a fascinating curiosity that the very first platform where temporal Kerr cavity solitons were observed[3] may also be the one to offer the best fundamental jitter performance. ❐

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Competing interests

The author declares no competing interests.

SPINTRONICS

Disordered exchange is biased

The magnetic properties of intercalated metal dichalcogenides are dramatically affected by small crystal imperfections, potentially providing design principles and materials for spintronic devices.

Minhyea Lee

Hysteresis in a ferromagnet refers to the history dependence of the magnetization upon sweeping an external magnetic field. When a thin ferromagnetic film is in contact with an antiferromagnetic one, the centre of the hysteresis loop moves away from zero field. This phenomenon is called exchange bias, and the exchange-bias field refers to the size of the shift along the magnetic field axis. Although the term first appeared in mid 1950s[1], it became widely known with the advent of ferromagnetic/antiferromagnetic multilayer thin-film studies. Writing in *Nature Physics*, Eran Maniv et al. report a giant exchange-bias field in an unexpected place, namely a disordered antiferromagnetic state hosted in the single-crystalline intercalated magnetic dichalcogenide Fe_xNbS_2 (ref. [2]).

The basic mechanism of the exchange-bias effect is that the magnetization direction in a ferromagnetic layer (free layer) can be pinned by an adjacent antiferromagnetic layer (pinning layer). In a properly crafted system, one can control the preferred direction of magnetization and switching field of the free layer, as shown in Fig. 1a. This is crucial in applications to prevent random noise from reversing the magnetization. Consequently, the exchange-bias phenomenon plays a key role in the design of spin-based electronics devices, which are now widely embedded in magnetic storage and memories. Despite its wide usage, a comprehensive understanding of exchange bias is a longstanding problem and there is a major effort to search for functional materials with optimal performance. Typically, this search has focused on parameters such as magnetic anisotropy, crystal structure, spin configuration, interface roughness and properties of magnetic domains in the thin-film geometry.

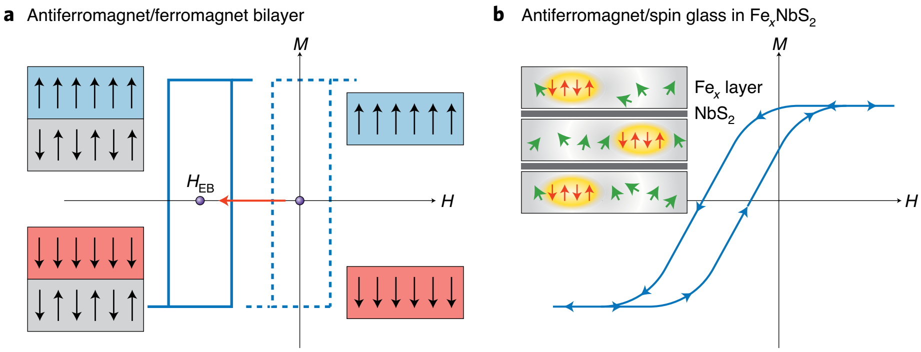

Fig. 1 | Exchange-bias field in an antiferromagnet/ferromagnet bilayer and Fe_xNbS_2. a, In a regular ferromagnet, the magnetization (M) switches at different magnetic fields depending on whether the field is ramped up or down (dashed lines). Pairing a ferromagnet with an antiferromagnet shifts the hysteresis loop, and the offset in the centre H_{EB} is the exchange-bias field. **b**, Schematic plot of the hysteresis loop in Fe_xNbS_2. The large exchange bias is attributed to the coexistence of two phases in the Fe_x layers that are separated by NbS_2, as schematically illustrated in the inset. A spin glass (green arrows) — a disordered phase that can have an overall net magnetization under an external field — coexists with antiferromagnetic order (red arrows).

Materials in the family of Fe_xNbS_2 are naturally existing magnetic multilayers, with layers of 3*d* transition metal atoms (the iron in this case) intercalated in a non-magnetic metal dichalcogenide lattice (here, the NbS_2). They exhibit a wide variety of magnetic properties, including various spin ordering patterns, transition temperatures and magnetic anisotropies, depending on the intercalated ion and host lattice[3]. For the stoichiometric composition of $x = 1/3$, the intercalated magnetic layer forms a superlattice where the magnetic ions sit in a triangular lattice. In $Fe_{1/3}NbS_2$, one has archetypical antiferromagnetic ordering at 42 K, with moments perpendicular to the layers.

Maniv and colleagues show that a large enhancement of exchange bias arises away from this stoichiometric composition, with approximately a 10% excess or deficiency of Fe ions. They observed that the excess or deficient ions form a spin-glass phase, while the underlying antiferromagnetic order persists. Figure 1b illustrates the schematic spin configuration in Fe_xNbS_2 and the shift in the hysteresis loop. The spin glass is an inherently disordered phase, yet it exhibits a large magnetic moment under field cooling, analogous to a ferromagnet. The giant exchange bias is then ascribed to the coupling to the underlying antiferromagnetic phase that has the role of a pinning layer.

The concept of exploiting disorder to produce a desirable effect can be applied across condensed-matter physics. Although disorder is often feared as a source of undesirable dissipation or loss of predictability in properties, here, the site disorder in Fe_xNbS_2 leads to frustration that introduces the spin-glass phase. In turn, the field-history-dependent nature of the spin glass coexists with the antiferromagnetic order parameter and is key to the enhanced exchange bias. Maniv and co-workers established the two-sublattice antiferromagnetic order using nuclear magnetic resonance measurements, and the spin-glass phase by presenting non-ergodic behaviour of the magnetization. The change of Fe composition x provides a means to tune the relative strength of the two coexisting orders.

This demonstration of the role of disorder in the physics of exchange bias in a single crystal is a breakthrough, but there has been previous work that looked at related effects in bilayers. For example, other work has shown that a bilayer of an elemental ferromagnet (cobalt) and a classic spin-glass system (copper-manganese alloy) demonstrates all the phenomena associated with exchange bias[4]. Together with the work of Maniv et. al., these results offer a compelling basis for more investigations on how bulk disorder impacts the exchange bias in devices. This may also translate into a new design strategy for magnetic film interfaces, where materials with inhomogeneous microscopic environments that induce frustration may support a larger exchange bias.

As bulk magnets, some magnetic dichalcogenides have been shown to display distinctive properties, while little attention has been paid to the context of exchange bias, or their potential as functional materials for spintronics applications. This leaves a large array of non-stoichiometric intercalated magnetic chalcogenides[3] to be explored with the possibility of exchange-bias phenomena due to disorder-induced glassy behaviour in mind. Similarly, there are single-crystalline bulk magnets, with substantial frustration, exhibiting coexistence of spin glass and antiferromagnetic order[5,6]. Studies of exchange bias in these systems will offer yet another perspective on the role of disorder and frustration in magnetic materials. ❐

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