insight into the general immunology of virus infection, as well as shed light on the strategies used by viruses and cancer to evade immune responses.

The association of EBV with cancer has been exploited for clinical benefits, with implications for the diagnosis and treatment of all cancers. The measurement of EBV DNA in the blood of people who have NPC provides a valuable prognostic biomarker and this can also be used as a screening test to detect early-stage NPC[8]. This approach provided the foundation for the development of technologies that measure tumour DNA in the bloodstream for the early detection of more-common cancers. Gaining a better understanding of the immune response to EBV led to the successful development of T-cell-based therapy for PTLD and other EBV-associated tumours, an approach that is now being more-widely explored for cancer therapy[18].

The association of EBV with multiple sclerosis has reignited interest in the possibility of both preventative and therapeutic vaccines that target EBV[13,19]. Original studies of a preventative vaccine against EBV demonstrated protection from infectious mononucleosis but not from the initial (primary) asymptomatic EBV infection. Achieving complete protection from EBV infection will probably require a more efficient immune response, such as one generated by the EBV vaccines currently under development that encode multiple virus proteins[20]. There have been many attempts to develop therapeutic vaccines for the treatment of EBV-associated cancers but with limited success. However, new approaches to vaccine development, particularly those using messenger RNA, hold promise for the both the prevention and treatment of EBV-associated diseases and are currently being tested in clinical trials[12,19,20].

The discovery of EBV 60 years ago led the way to firmly establishing that viruses can cause cancer in humans. Aside from shedding light on the role of infection in cancer, EBV's intimate relationship with the immune system has provided valuable insights into the regulation of immune responses. Another downside of this close interaction is EBV's contribution to multiple sclerosis and possibly to other autoimmune diseases. Efforts to develop effective vaccines and antiviral drugs raises hope for the prevention and management of EBV-associated diseases and for the wider elimination of all cancers caused by viruses.

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Condensed-matter physics

Magnetic whirlpools offer improved data storage

Qiming Shao

Complex magnetic structures called skyrmions have been generated on a nanometre scale and controlled electrically — a promising step for fast, energy-efficient computer hardware systems that can store large amounts of data. **See p.522**

Every electron has an intrinsic angular momentum known as its spin, and the direction of this spin — either up or down — is used to store the bits of information that make up hard-disk drives and magnetic tapes. But these bits are moved by rotating the host material mechanically, which is slow and can be unreliable. Magnetic skyrmions are complex whirlpool-like arrangements of spins that can be controlled electrically on a nanometre scale, making them promising candidates for storing large amounts of data that can be accessed rapidly[1]. On page 522, Chen *et al.*[2] report an all-electrical way to read and write information by encoding it in a single nanoscale skyrmion, paving the way for low-power data storage on a massive scale.

The ability to control a magnetic state electrically is made possible by a phenomenon called giant magnetoresistance. This Nobel-prizewinning discovery kicked off the research field known as spintronics[3]. Giant magnetoresistance is a huge change in electrical resistance that is induced by a change in the magnetic state of a material, and it occurs in multilayer systems that comprise at least two magnetic layers separated by one non-magnetic layer. When the spins in the two magnetic layers point in the same direction, the system has a low resistance; when they point in opposite directions, the system has a high resistance. This difference in resistance — usually less than 20% at room temperature[3] — determines how easily one can distinguish between the two configurations.

A related phenomenon called the tunnel magnetoresistance effect can bring about a difference of more than 100%. This effect can be induced in magnetic tunnel junctions — structures that consist of a non-magnetic layer sandwiched between two magnetic layers (Fig. 1a). The spins in one magnetic layer are pinned to point upwards, whereas those in the other layer can be switched between up and down by applying an external magnetic field or a voltage, resulting in configurations that are parallel and antiparallel to the pinned spins, respectively. The latest hard-disk drives and magnetic tapes use this principle to read magnetic states quickly and reliably. But writing magnetic states still requires mechanical rotators to position the magnetic bits that need to be written, resulting in slow speeds, high energy costs and low reliability.

Skyrmions could provide a solution: these intricate spin textures can be driven by an electrical current[1], so a magnetic tunnel junction that has a skyrmion in the place of the switchable (free) spin layer could enable rapid and efficient reading and writing of information. But this would require nanoscale skyrmions to be generated at room temperature in a structure that has high tunnel magnetoresistance — a feat that has proved elusive despite some admirable efforts[4,5]. So far, only large skyrmions have been induced in such structures[6], and

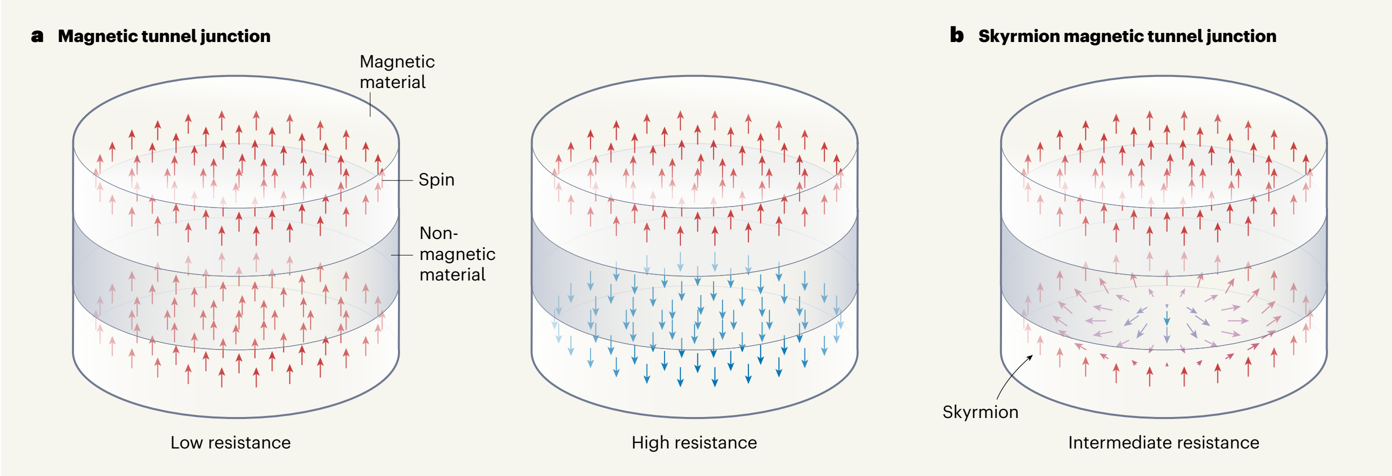

Figure 1 | Storing data with magnetic whirlpools. Information can be encoded in the spin (intrinsic angular momentum) of electrons in a magnetic material. **a**, A structure called a magnetic tunnel junction comprises a non-magnetic layer between two magnetic layers, one with spins that are pinned to point upwards and the other with spins that are free to rotate. Electrical resistance across the structure is low when the spins in the free layer point upwards, and high when they point downwards. This difference can be used to detect the magnetic state, which stores information. **b**, Chen *et al.*[2] engineered the free layer in a magnetic tunnel junction to have a single skyrmion, which is a whirlpool-like arrangement of spins. In this state, the resistance took an intermediate value, and the authors could switch between low and intermediate resistance and between intermediate and high resistance by applying a voltage.

nanoscale skyrmions have been generated in structures that do not have high tunnel magnetoresistance[7]. However, Chen *et al.* have managed to create a hybrid structure that can host a nanoscale skyrmion and simultaneously maintain high tunnel magnetoresistance.

The skyrmion appeared in the authors' structure at an intermediate state while the spins were being flipped between the low-resistance (up) state and the high-resistance (down) state, a reversal that was induced by using an applied voltage or an external magnetic field. Chen *et al.* measured the resistance of their magnetic tunnel junction in this intermediate state and found that it lay between the low and high values associated with the up and down spin states. By changing the voltage or the external magnetic field, the authors could reversibly switch the resistance from low to intermediate or from intermediate to high. The difference between the intermediate resistance and the high or low resistance could be as large as 70%, which is much bigger than that reported in previous attempts involving multiple skyrmions[4,5].

The authors imaged the spins inside their skyrmion magnetic tunnel junction using a magnetic force microscope, which can probe spins with nanoscale resolution by sensing the magnetic force they exert on a tiny magnetic tip. The microscopy images revealed that there was indeed a single skyrmion in the intermediate state – the spins in the centre of the whirlpool were pointing downwards and those on the edge were pointing upwards (Fig. 1b). By combining experiments with micromagnetic simulations, Chen *et al.* showed that the production of this skyrmion was made possible by a magnetic field that was generated by the spins in the pinned layer. They also found that the skyrmion state was stable, even when no external magnetic field was applied.

Because the switching process that Chen *et al.* used was voltage driven, it consumed much less power than conventional ways of creating skyrmions – typically current driven[1,6]. This strategy works because the applied voltage modifies a property of the free-spin layer known as its perpendicular magnetic anisotropy, which is crucial for maintaining the thermal stability of the up and down states. Applying a positive voltage destabilizes the magnetic state and causes it to switch, but the outcome of the switching cannot usually be controlled easily. This effect has already been used to create a kind of random-access computer memory, but the technology is currently associated with a high 'write error' rate[8].

Chen *et al.* engineered their structure so that a positive voltage reliably induced the skyrmion state by making an interaction that aligns neighbouring spins more strongly than does the effect of perpendicular magnetic anisotropy. When they applied a negative voltage, the reverse was true, making the skyrmion state less energetically favourable than either the up or down state. This voltage-driven switching makes information writing 1,000 times more energy efficient than can be achieved with current-driven switching.

The authors' demonstration of an all-electrical skyrmion magnetic tunnel junction is a key step on the path to practical skyrmion-based data-storage devices. However, the magnetization switching implemented by Chen *et al.* is assisted by external magnetic fields, so field-free methods still need to be developed to achieve optimal writing. Furthermore, the authors' scheme does not provide a way to move skyrmions around – a task that must be undertaken by another device, one that is current-driven. There is, therefore, a need for a unified approach to writing, shifting and reading skyrmions with a single device[9]. Finally, an improved understanding of the thermal stability of skyrmion magnetic tunnel junctions would be beneficial, as would further investigation of the potential for ultrafast switching with these devices.

Aside from being a long-awaited achievement in condensed-matter physics, the realization of a skyrmion magnetic tunnel junction could unlock opportunities in brain-inspired computing[10–12]. In particular, magnetic tunnel junctions and skyrmions could both take the roles of synapses and neurons in artificial neural networks[10–12]. Chen and colleagues' combination of these two computing elements, therefore, has exciting implications for future developments in unconventional computing.

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