narrow energy spectrum, and the scattering leads to a large broadening up to 20 keV. Considering that the optical grating has a period of 1.4 μm, this corresponds to a diffraction order of more than 30,000, or that the fastest electrons have been kicked 30,000 times by the optical grating. This acceleration occurs over only a few micrometres, which corresponds to an acceleration gradient of 2.2 GeV m⁻¹, comparable with other types of laser accelerators in vacuum⁴ and much larger than radiofrequency acceleration. There are also temporal features associated with this longitudinal scattering. Because the energy is absorbed in quanta by the electrons, the energy spectrum is actually composed of a broad comb, which translates into a temporal comb of electron wavepackets — a series of short electron pulses separated by approximately 15 femtoseconds. These pulses reach a minimum duration shortly after the interaction, each one being about 200 attoseconds long. Even though dispersion extends this duration quickly, temporal compression stages could be added in order to exploit this temporal comb for phase-resolved measurements in electron microscopy.

The experiment presented by Kozák et al. is a new type of non-resonant, nonlinear optics experiment where a single free electron acts as the nonlinear medium. This creates exciting opportunities in fundamental investigations of the quantum nature of nonlinear interactions between light and free electrons, where the electron spin and orbital angular momentum could also play a role. The reported experiment also places the generation of isolated attosecond electron pulses by sophisticated compression schemes within the reach of the currently available laser systems.

Figure 1 | Electron wavepackets are generated by an ultraviolet femtosecond laser pulse from a Schottky tip and accelerated to 29 keV. They collide with a travelling optical grating formed by the interference of two synchronous infrared laser pulses at different wavelengths with an angle. Thanks to a type of Kapitza–Dirac effect, the electrons are kicked forward or backward by two-photon processes, like balls in a pinball game. This results in a temporal comb of attosecond electron wavepackets. The inset shows the final kinetic energy spectrum of the electrons with a broad spectrum of about 20 keV. Adapted from ref. 2, Macmillan Publishers Ltd.

Benoît Chalopin is at Université de Toulouse, 31062 Toulouse, France. Arnaud Arbouet is at CEMES–CNRS, 31055 Toulouse, France. e-mail: benoit.chalopin@irsamc.ups-tlse.fr; arnaud.arbouet@cemes.fr

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TOPOLOGICAL VALLEYTRONICS

Brought to light

The topological valley Hall effect was predicted as a consequence of the bulk topology of electronic systems. Now it has been observed in photonic crystals, showing that both topology and valley are innate to classical as well as quantum systems.

Fan Zhang

Valleys — the degenerate energy extrema in the band structure of a material — have recently emerged as novel carriers of information and energy, much like charge and spin. And just like electrons with opposite spin, electrons in opposite valleys can counter-propagate along the edge of a two-dimensional insulator without any dissipation¹². These symmetry-protected topological effects are usually associated with quantum systems, but classical waves can possess
a valley degree of freedom, too. So even though they can carry neither charge nor spin, classical systems should be capable of hosting such exotic topological effects. Now, writing in *Nature Physics*, Fei Gao and co-workers’ report the unambiguous observation of topological valley transport of electromagnetic waves along a domain wall in a honeycomb photonic crystal.

In 1879, Edwin Hall discovered that when an electric current flows through a thin, flat conductor under a perpendicular magnetic field, the moving charge carriers are deflected to one side of the conductor by the Lorentz force (Fig. 1a). Fundamentally, it is the breaking of time-reversal symmetry that leads to this Hall effect. In 2004, Charles Kane and Eugene Mele predicted a quantum version of a related effect (Fig. 1d): a topological insulator that has an odd number of pairs of counter-propagating edge states with opposite spin (Fig. 1e). In this case, the time-reversal symmetry is unbroken and plays an essential role in protecting this quantum spin Hall effect. Now, the idea of utilizing the combination of symmetry and topology has also inspired the design of novel functionalities in photonic, mechanical and sonic systems.

Analogous to the quantum spin Hall effect, topological valley Hall effects were proposed for the situation where the valley is a good quantum number (Fig. 1f). In the quantum spin Hall effect, the time-reversal symmetry does not require spin conservation. By sharp contrast, the valley needs to be a good quantum number in order to validate the bulk topological invariant — the valley Chern number — which corresponds to the number of inter-valley or lattice-scale scattering needs to be negligible weak both in the bulk and at the edge. This poses a serious challenge in electronic experiments where often the edge termination or reconstruction will strongly mix the two opposite valleys.

For bilayer graphene with a bandgap induced by an external electric field, very smooth domain walls (Fig. 1h) that either switch the layer stacking orders or reverse the electric field orientation have been used to produce a change of the bulk valley Chern number while minimizing the inter-valley edge backscattering. Indeed, metallic mid-gap states have been experimentally observed along such domain walls, and their conductance has appeared to approach two conductance quanta. However, its full quantization is still under debate. For similar systems without the smooth domain walls, only considerable non-local resistance that scales cubically with local resistance has been detected. It is most likely that the mid-gap edge states have become gapped and passivated toward the bulk band edges due to the inevitable inter-valley edge backscattering.

The work done by Gao *et al.* represents an important step in realizing valley Hall effects, provides evidence for their topological origin, and thereby settles the debate in the electronics community. For both transverse electric and transverse magnetic modes, the valley Chern number changes by one across the valley-preserving zigzag domain wall in their photonic crystal. Indeed, they observed that there is one pair of edge states counter-propagating in the two opposite valleys for each mode and that they can be easily tuned and selectively excited. By refracting these valley-projected chiral modes into free space, they showed that the reflectance is, on average, less than 0.1% across the entire bandgap and independent of the detailed shape of domain wall.

Due to the high efficiency of the coupling between the topological modes and free-space modes, it is tempting to envisage practical valleytronic applications in directional antennas, lasers and other communication devices across the electromagnetic spectrum. More fundamentally, the in-phase and out-of-phase relations between the transverse

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**Figure 1** | Geometric and topological Hall effects. **a-c**, Schematics of the charge, spin and valley Hall effects in the bulk of 2D systems. **d-f**, the topological counterparts of **a-c**: each displays a bandgap in the 2D bulk and protected gapless states at the 1D edge, as a consequence of the nontrivial bulk topological invariant. Respectively, \( C \), \( Z \), and \( C_v \) are the first Chern number, the Kane–Mele index and the valley Chern number. **g**, Schematic band structure of a system that exhibits the topological valley Hall effect in **h**. The boundary between crystal \( (C_v = N) \) and vacuum \( (C_v = 0) \) in **f** replaced by a smooth domain wall between two topologically distinct crystals \( (C_v = \pm N/2) \) to reduce the inter-valley edge backscattering that may passivate the counter-propagating valley-projected chiral edge states. We have chosen \( N = 1 \) to illustrate the edge states in **d** and **f-h**.

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magnetic and transverse electric modes can be exploited to emulate the spin degree of freedom and then introduce an analogue of spin–orbit couplings for electromagnetic waves. This would greatly enrich the topological features of the photonic honeycomb crystal and possibly enable distinct classes of topological photonics.

Together with other works in electronic and sonic systems, the work of Gao et al. suggests that the topological valley Hall effect is universal to both quantum and classical waves. Various valley-projected edge states originating from band topology exist not only in quantum solids but also in artificial crystals. Amazingly, the equatorial ocean and atmospheric waves share a similar topological origin. As a final remark, like the spin Hall effect (Fig. 1b), the valley Hall effect can also be geometric, distinct from the topological phenomena discussed here. In the geometric valley Hall effects (Fig. 1c), bulk wavepackets such as excitons can bifurcate due to the presence of valley-dependent Berry curvature.

The discovery of counterflow in opposite valleys not only demonstrates that the valley can be a novel carrier of information and energy — particularly valuable for systems without charge and spin — but also exemplifies that symmetry-protected band topology can be universal to both quantum and classical systems. This result is truly elegant and inspiring.

Fan Zhang is in the Department of Physics, University of Texas at Dallas, Richardson, Texas 75080, USA.
E-mail: zhang@utdallas.edu

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COLD MOLECULAR COLLISIONS

Same object, different symmetry

Cold collisions between hydrogen molecules and helium atoms reveal how the change from spherical to non-spherical symmetry creates a quantum scattering resonance.

Roland Wester

Sports enthusiasts know the ambiguity of the term football: in the UK, it’s the sport played with a spherical ball, whereas in the US, it’s a very different game played with a ball of somewhat elliptical symmetry. On the atomic scale, there’s a similar — but not only purely linguistic — ambiguity surrounding hydrogen. Molecular hydrogen, the diatomic molecule composed of two (spherically symmetric) hydrogen atoms, is a linear molecule with an electron density distribution that is cylindrically symmetric with respect to the interatomic bond axis. However, molecular hydrogen can not only act as an aspherical ellipsoid, but also as a spherical object when in its rotational ground state — as if stopping an American football from spinning would turn it into a soccer ball. Quantum mechanics explains why: the wave function of a molecule with zero rotational angular momentum can only be spherically symmetric. Writing in Nature Physics, Ayelet Klein and colleagues now show that this fundamental quantum effect can actually be observed. The authors demonstrate how the change from spherical to non-spherical symmetry qualitatively affects the collision dynamics with metastable, electronically excited helium atoms. In a combined experimental and theoretical study, they characterized a low-temperature quantum scattering resonance that only appears if the anisotropic interaction of non-spherical hydrogen is present.

Around room temperature, collisions between atoms and molecules occur at such high collision energies that they are usually not sensitive to variations in the long-range part of the interaction potentials. The strong interatomic forces at short distances, which always depend on the relative orientation between molecule and atom, determine the collision outcome. It is at low temperatures that the fact that a spherical hydrogen molecule only interacts via a van der Waals potential becomes important; a non-spherical hydrogen has an electric quadrupole moment that can interact with the induced dipole in helium. As illustrated in Fig. 1, this leads to a change in the interaction potential by at most one kelvin. Also, at low temperatures, the number of angular momentum states of the collision system becomes limited. This different, low-T regime of molecular interactions has been the driving force of the emerging field of cold molecular collision physics and cold chemistry. In recent years, many schemes have been developed for experimentally preparing cold molecules in controlled quantum states and accessing the cold molecular collision regime. With the advent of merged-beam techniques for cold molecules a few years ago, the stage has finally been set for investigating cold molecular collisions at well-controlled relative energies.

Klein et al. chose two elementary species for their study: hydrogen and helium. To make the collision highly reactive, the helium atoms were prepared in the long-lived metastable triplet state by means of electron-impact excitation in a pulsed discharge. Close encounters with hydrogen then led to Penning ionization and the resulting hydrogen molecular ions were detected one by one. The helium triplet state has another important feature: its Zeeman effect in an external inhomogeneous...