the coordinates allows other researchers to test structural models with their own experimental and theoretical techniques. Depositing CIF files is common practice in crystallographic journals, and surface scientists are well advised to adopt this habit.

The results of Enterkin *et al.* should be of wide interest: they not only solve a complex surface reconstruction of an important metal oxide, the work also showcases both the techniques and concepts used routinely by inorganic chemists. With the interest shifting to more and more complex oxides, several strategies are needed to resolve their surface structure and other properties. ❒

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TOPOLOGICAL INSULATORS

Oscillations in the ribbons

The observation of Aharonov–Bohm oscillations in nanoribbons of Bi_2Se_3 opens the way for electronic transport experiments in nanoscale three-dimensional topological insulators.

Thomas Ihn

Topological insulators[1] have risen to the attention of the scientific community only in the past few years. They are different from both insulators and metals because, whereas the bulk exhibits a finite electronic bandgap, and is therefore insulating, the surface states are gapless and metallic. Two- and three-dimensional variants of this class of materials have been studied experimentally and theoretically. The gapless metallic states at the surfaces are predicted to lead to unusual transport properties. However, transport experiments have so far been hampered by insufficient control over the bulk. In particular, unintentional and uncontrolled doping leads to residual conductance that masks that of the surfaces. As reported now in *Nature Materials*, Hailin Peng, Keji Lai and co-workers have succeeded in accessing the surface conductance of the topological insulator Bi_2Se_3 by fabricating nanoribbons, thus increasing the surface-to-volume ratio[2]. This approach allowed the observation of Aharonov–Bohm oscillations, which represents the first demonstration of quantum interference in the transport properties of this new class of materials.

The Aharonov–Bohm effect[3] is related to the interference of two coherent electron beams. It has been known[4] at least since the 1940s that a magnetic flux enclosed by the two interfering partial waves (Fig. 1a) changes their relative phase and can thereby turn constructive interference into destructive, and vice versa. According to the theoretical prediction, the interference pattern is periodic in integer units of the magnetic flux quantum h/e, where h is Planck's constant and e is the elementary charge. A higher-order variant of the effect can occur if a single path takes one full turn around the flux tube (see one of the paths in Fig. 1b). A pair of paths differing only in the direction in which it is taken (that is, clockwise or anticlockwise, see Fig. 1b) is related by time reversal, because the velocities would be inverted if the time ran backwards. Interference of pairs of time-reversed paths is periodic in units of half the magnetic flux quantum $h/2e$.

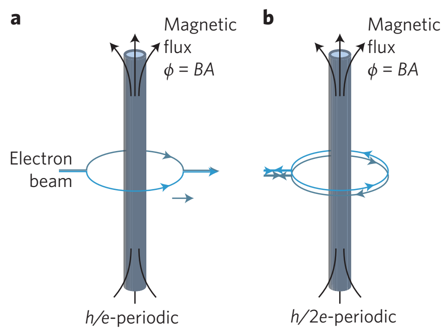

Figure 1 | Aharonov–Bohm oscillations. **a**, If the two interfering partial waves represented by the blue arrowed lines enclose the magnetic flux once, the intensity of the beam transmitted to the right will be modulated with period h/e. The magnetic flux (ϕ) may be seen as a homogeneous magnetic field B within the area A of the flux tube. **b**, If the two interfering partial waves are a pair related by time-reversal, each encircling the magnetic flux once, the reflected intensity will always be a maximum at zero flux, and it will be modulated with period $h/2e$.

In the 1980s the Aharonov–Bohm effect became well known in the field of mesoscopic electron transport, in which conductance is regarded to be proportional to electron transmission[5,6]. Sharvin and Sharvin[7] measured the conductance of a long and thin magnesium cylinder evaporated around a micrometre-thin quartz filament (Fig. 2a). With the magnetic field oriented along the axis of the cylinder they found periodic oscillations in the magnetoconductance with a period given by $h/2e$, normalized to the cross-sectional area of the cylinder. In the same year, oscillations with this period had been predicted theoretically[8]. Similar results were later obtained in carbon nanotubes (Fig. 2b)[9]. The reason why in these experiments the h/e-periodicity was not observed was explained by various studies on metals[10] and semiconductors[6], for example on ring-shaped planar geometries and arrays of rings. Briefly, pairs of paths contributing to the fundamental h/e period have a specific relative phase at zero magnetic field. If many such pairs with uncorrelated zero-field phases contribute to transport, the h/e oscillations average out. In contrast, the $h/2e$-periodic oscillations contain a significant contribution of time-reversed paths, which all have the same relative phase of zero at the interference point, and are therefore robust against averaging.

The experimental specimen of Hailin Peng, Keji Lai and co-workers[2] resembles that of the Sharvin and Sharvin experiment[7], as shown schematically in Fig. 2c. In the topological insulator

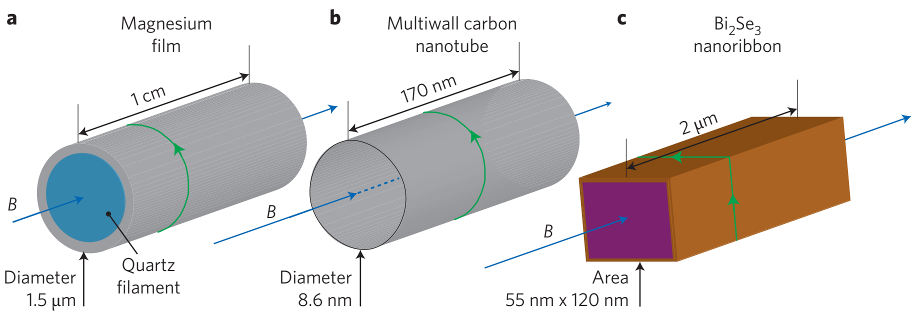

Figure 2 | The similarity between different experiments on tube-like geometries. **a**, Geometry of the Sharvin and Sharvin experiment[7], in which a magnesium film was evaporated onto a quartz filament. **b**, Experiment on a carbon nanotube[9], where electron motion is confined to the cylindrical surface of the tube. **c**, The new experiment reported by Peng, Lai and co-workers[2], whereby a significant contribution to transport stems from the gapless surface states of the Bi_2Se_3 nanoribbon.

however, there is no need for an insulating core and a conducting surface, because the material itself has these characteristics. The interpretation of the new experiment is that the thin nanoribbon geometry reduces the bulk conductivity caused by crystal defects to an extent that allows the signature of the Aharonov–Bohm-type oscillations of surface states to be observed, if a magnetic field is applied along the ribbon axis. The observation of the fundamental h/e period surprisingly indicates the absence of strong self-averaging in these experiments. Peng, Lai and colleagues argue that in the Bi_2Se_3 nanoribbons the topological protection helps to bring about the fundamental period of the Aharonov–Bohm interference at small magnetic fields, rather than the more robust $h/2e$ period seen in the magnesium cylinders, and in carbon nanotubes.

Present research on topological insulators is still at an early stage, but has the potential to have a bright future. Perhaps nature will provide us with even more materials belonging to this class. Improving the quality of the available materials represents a significant challenge. Nanoribbons made of three-dimensional topological insulators could be natural competitors of today's core–shell nanowires grown epitaxially with great precision and high quality. But two-dimensional topological insulators will also contribute to future research: edge-channel transport in the two-dimensional heterostructure HgTe/HgCdTe, which is a zero magnetic-field topological insulator, has been demonstrated recently[11], and Aharonov–Bohm-type oscillations have been seen in this material. Two-dimensional topological insulators have also been proposed in single- and double-layer graphene. Visionary proposals see applications in spintronics, valleytronics or even topological quantum computation, for example with the exotic fractional quantum Hall state at filling factor 5/2 (ref. 12). Although the realization of these goals will be highly challenging, it will no doubt spark a great variety of new basic research on nanoscale structures at the interface between physics, materials science and electronic engineering. ❐

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MULTIFERROICS

A whirlwind of opportunities

The formation of vortices in multiferroic hexagonal manganites, where the sign of electric polarization changes six times around the vortex core, points towards the origin of composite multiferroic domain walls.

Maxim Mostovoy

Multiferroic materials with their coexisting ordered states of electric and magnetic dipoles may find use in many technological applications — such as magnetoelectric random-access memory — that excel by virtue of their low power consumption[1]. One of the key milestones on the way to achieving this goal was the demonstration of remarkable control of electric polarization by an applied magnetic field in a number of compounds in which the electric dipoles are induced by ordered electron spins[2].

Another promising route towards magnetoelectric switching relies on the unusual properties of defects in multiferroic orders[3]. In particular, in the hexagonal manganite $YMnO_3$, nonlinear optical studies show that ferroelectric domain walls are firmly locked with the magnetic domain walls[4] forming composite multiferroic domain walls. This observation is very surprising at first because the sign of electric polarization is independent of the orientation of the magnetic spins and vice versa.

Writing in *Nature Materials*, Taekjib Choi and colleagues now report[5] the discovery of a missing component that is crucial to the understanding of this domain-wall clamping. The authors combine transmission electron microscopy (TEM), which enables them to observe the six different structural domains of $YMnO_3$, with conductive atomic force microscopy (CAFM), which they use to measure the polarization of the ferroelectric domains. These experiments reveal that the ferroelectric and structural domains