OPTICS

Topology, spin, and light

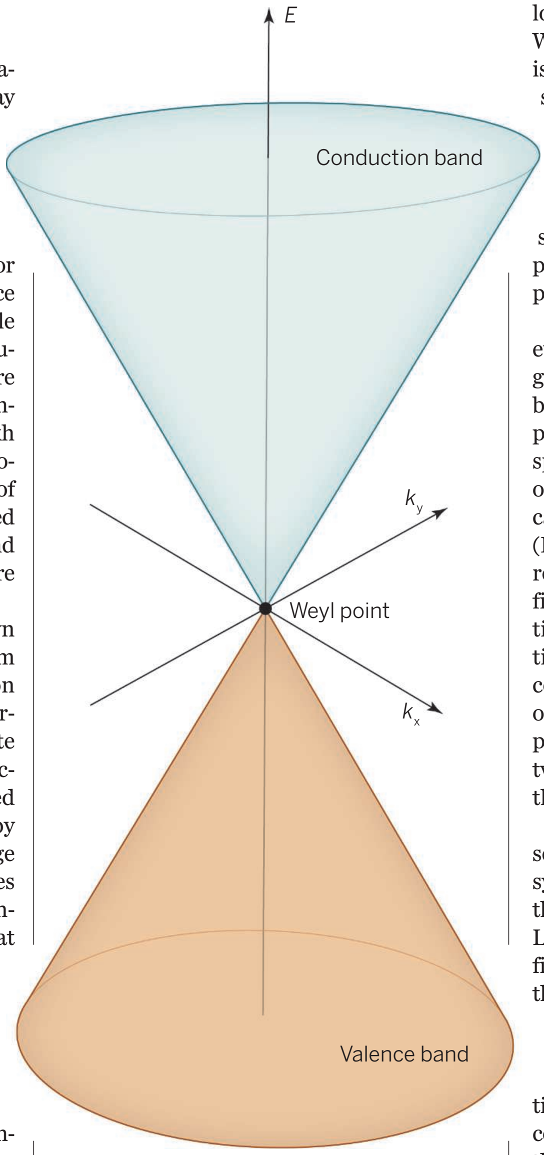
Evanescent solutions to Maxwell's equations correspond to surface modes with strong spin-momentum locking

By **Michael Stone**

Ocean waves form between air and water, and both winds and currents decay exponentially with distance from the water surface. Similar evanescent surface waves may occur whenever two substances with differing physical properties meet—but some are special cases because they must exist for topological reasons. Such mandated surface modes occur in the low-energy quasiparticle spectrum of p-wave superconductors and superfluids and constitute the defining feature of the electronic properties of topological insulators. On page 1448 of this issue, Bliokh *et al.* (*1*) suggest that we add evanescent solutions of Maxwell's equations to this list of special cases, and in particular, the coupled oscillations of the electromagnetic field and the near-surface electrons in a metal that are known as surface plasmon-polaritons.

These optical modes have been known for some time; what is new here is the claim that they bear a close analogy to electron waves of topological origin. Topological surface modes in electronic systems originate in the way in which the Bloch wave functions in the bulk of the material are linked together. This linking is characterized by topological invariants that cannot change unless some interband energy gap closes (for example, if the energy levels of the conduction and valence band electrons cross at some particle momentum).

In topological insulators (*2*), there is an energy gap between the valence bands occupied by electrons and the empty conduction bands. The bulk of the material is an insulator, but the surface states have no energy gap and the surface is conducting. The gaplessness arises because the linking means that we cannot break the solid into a collection of disconnected atoms without closing the energy gap. The outside of the material looks to the interior electrons as a disconnected part, so the gap must close at the surface.



A Weyl point. The energy-momentum relation near a Weyl point is seen in the surface states of a topological insulator, the bulk states of a Weyl semimetal, the evanescent plasmon-polaritons, and the theoretical study of Bliokh *et al*. Near such a point with momentum $\mathbf{p} = \mathbf{p}_0$, the energy is given by $E(\mathbf{p}) = \pm\text{const.}\,|\mathbf{k}|$, where $\mathbf{k} = \mathbf{p} - \mathbf{p}_0$.

The low-energy surface electrons typically obey a Weyl equation, which is the "half-Dirac" equation that describes massless neutrinos with a definite handedness. The graph of the energy versus momentum of a particle obeying the Weyl equation forms a cone with the positive and negative energy state touching at a single "Weyl point" (see the figure). A full Dirac equation for massless particles falls apart into a pair of Weyl equations with opposite handedness. Adding a mass term to a Dirac pair of Weyl fermions couples the left- and right-handed modes and opens a gap between the upper and lower cones in the energy spectrum. In the absence of an opposite-handed Weyl mode, no gap can open. Weyl equations also appear in a class of topological materials called Weyl semimetals (*3*). In this case, the low-energy electrons in the interior obey Weyl equations. In a Weyl semimetal, there is an even number of points in momentum space where the conduction and valence band touch and where the wave functions obey a Weyl equation. These materials also have gapless surface states, where the momenta of the zero-energy states lie on "Fermi arcs" that connect the projections of left- and right-handed Weyl points onto the surface.

Interest in the topological character of evanescent optical modes arises from a growing appreciation of the close resemblance of the wave equations for the spin-1 photon and the spin-½ electron—and how spin has similar effects on the dynamics of both. The free-space Maxwell equations can be rewritten in "Riemann-Silberstein" (RS) form (*4*) where four equations for the real-valued electric field **E** and magnetic field **B** reduce to two complex-valued equations, one for the right-handed combination $\mathbf{E} + ic\mathbf{B}$ and one for the left-handed combination $\mathbf{E} - ic\mathbf{B}$, where c is the speed of light. The RS equations look like a Dirac pair of Weyl equations except that two-by-two spin-½ Pauli matrices are replaced by three-by-three spin-1 equivalents.

As a result of their close resemblance, the semiclassical equations of motion for both systems contain anomalous velocity terms that are momentum-space analogs of the Lorentz force, but with the electromagnetic field replaced by the same Berry curvature that provides the topological invariant in the Weyl semimetals. In particle physics and condensed matter systems, this anomalous velocity is responsible for the violation of Liouville's theorem on phase space conservation at a Weyl point, and hence for the chiral anomaly that violates the separate conservation of the number of left- and right-handed particles even in the absence of a mass (*5*). In optics, the anomalous velocity is responsible for the spin-Hall effect of light and related effects (*6*).

A key characteristic of topological surface states is that the spin degree of freedom is locked in a fixed relation to the direction of the momentum. This same feature appears in all evanescent wave solutions to Maxwell's equations. Furthermore, the solution to each of the right- or left-chirality free-space RS equations has topological invariant or Chern

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Department of Physics, University of Illinois, Urbana, IL 61801, USA. E-mail: m-stone5@illinois.edu

number $C = 2$ (twice as large as the $C = 1$ of the spin-½ equation), which again suggests that the boundary of free space should host topological modes.

Evanescent electromagnetic waves are trapped at any surface where the sign of one or both of the permittivity ε or the permeability μ changes from positive to negative and so couples the left- and right-handed Weyl-like equations. A sign change in ε occurs, for example, at the surface of a metal at frequencies below the electron plasma frequency ε_p, and the resulting modes are the surface plasmon-polaritons. These modes have a nonzero spin angular momentum that always lies to the right of their direction of propagation. This spin-momentum locking leads to fascinating directional scattering effects when the plasmon-polaritons run into surface defects (*7*).

In the topological interpretation, the interior or "bulk" of the topological system is free space, so the RS system is an analog of a Weyl semimetal (see the figure). It is really a Dirac semimetal (*8*), where the two Weyl points coincide to make a Dirac point. There can be no Fermi arcs connecting these coincident points. Instead, the low-energy polariton modes appear to connect the zero-momentum Dirac point with another Dirac point at infinite momentum.

Surface states are intimately connected with anomalous conservation laws: In topological insulators, a Berry curvature gives rise to Hall-like currents in the bulk, and where these currents meet the surface, they donate their spin or electric charge to the surface states. The bulk is invisible to the surface states because they cannot access it. To the surface states, the arriving charge anomalously violates the conservation of charge or spin (*9*). In a Weyl semimetal, there are anomalies at each Weyl point where particles can flow to the conduction band from the valence band, or vice versa. In this case, the semimetal Fermi arcs are there to provide the return flow on the surface (*10*). It is interesting to speculate that a similar interpretation might be found for the optical surface modes. ■

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GENE REGULATION

A HUSH for transgene expression

A protein complex represses genes that insert into heterochromatin

By **Thijn R. Brummelkamp**[1] *and* **Bas van Steensel**[2]

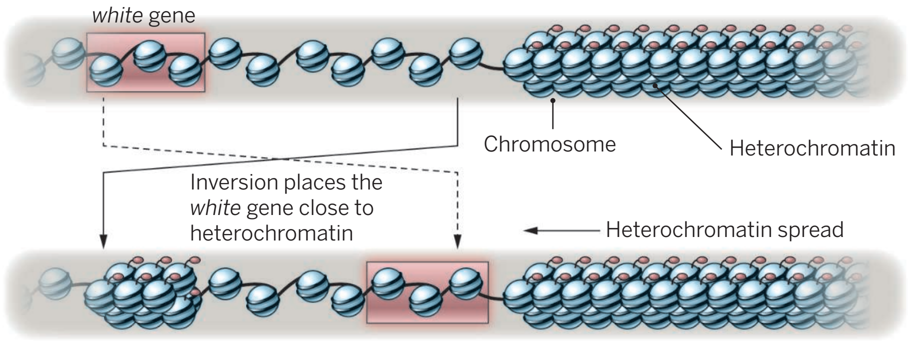
The introduction of an extra gene into a genome—transgenesis—is frequently used as an experimental approach to study gene function but also has applications in biotechnology and gene therapy efforts. In mammalian cells, transgenes are often integrated in a random manner leading to variable levels of expression, with differences as great as three orders of magnitude depending on the integration site (*1*). The complications of unpredictable levels of transgene expression are well recognized, but the mechanisms leading to variable expression are poorly understood. On page 1481 of this issue, Tchasovnikarova *et al.* (*2*) determine that a protein complex silences extra genes that are inserted into heterochromatin, regions of compacted DNA. This represents a new aspect of gene regulation that depends on chromatin context.

The prevailing thought is that the local chromatin environment at the site of transgene integration affects its activity. Gene introduction in the fly *Drosophila melanogaster* and other model organisms can lead to heterogeneous expression levels, referred to as position-effect variegation. In position-effect variegation, the transgene is thought to be silenced as a result of spreading of heterochromatin from neighboring sequences into the transgene (see the first figure). It remains unclear to what extent this relates to transgene silencing in mammals, and whether transgenes are silenced through multiple mechanisms or a dominant process operational at many different genomic locations.

Tchasovnikarova *et al.* took a genetic approach to identify regulators of transgene silencing in human cells, using a retrovirus to integrate the transgene into the genome. Random integration of a green fluorescent protein (GFP) reporter transgene into the human cell line resulted in cells with highly divergent GFP expression levels. The authors purified the subpopulation of cells with very low GFP expression, which they presumed was the result of transgene repression. To identify proteins responsible for this repression, they subjected these cells to random mutagenesis. Here, a key trick was the choice of human KBM7 cells as a model system (*3*): These cells are almost completely haploid, and hence a single mutation in a gene can have a profound effect because there is no second copy of the gene. Tchasovnikarova *et al.* collected the mutant cells in which GFP was thus reactivated and used high-throughput sequencing to identify the mutated genes.

This approach identified genes encoding the proteins SET domain, bifurcated 1 (SETDB1), transgenic activation repressor (TASOR), M-phase phosphoprotein 8 (MPP8), and periphilin. Through biochemical approaches, the authors found that the latter three proteins form a complex dubbed the human silencing hub (HUSH). This complex in turn interacts with SETDB1 (see the second figure). Thus, the results of the genetic screen nicely dovetailed with biochemical data.

Previously, all three HUSH subunits, among numerous other factors, were



Classic position-effect variegation. An early observation in *Drosophila* involved a chromosomal inversion in which an active eye color gene (*white*) is brought into close proximity to a heterochromatic chromosomal region, leading to repression of *white* by the spreading of heterochromatin into the gene.

ILLUSTRATION: C. BICKEL/SCIENCE

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