over just one transition state (TS1), and path 2 is a counterclockwise looping that surmounts two transition states (TS2 and TS3) (see the figure). The oscillations observed must be caused by interference between the two pathways. Specifically, Xie *et al.* examined the oscillations in backscattering as a function of energy. The scattering wave functions ψ for each path can be written as $\psi_1 = (\psi_{NGP} + \psi_{GP})/\sqrt{2}$ and $\psi_2 = (\psi_{NGP} - \psi_{GP})/\sqrt{2}$, respectively, and similarly rewritten for the respective scattering amplitudes. Using the backscattering amplitudes calculated with NGP and GP, they derived the moduli and phases of the scattering amplitudes for path 1 and path 2.

The authors found that the relative phases for the two paths are almost the same until the collision energy reaches 1.3 eV. For higher energies, the phases diverge, rapidly decreasing for path 1 and increasing for path 2, which gives rise to fast oscillations in the energy dependence of backscattering. From this analysis, it became apparent that the oscillations, as a function of the energy predicted by the NGP and GP calculations, are caused by the interference between the two pathways. Moreover, the analysis shows that there is a phase difference between NGP and GP oscillations of precisely 180°.

Quasi-classical trajectory calculations by Xie *et al.* and in previous studies (*6*, *7*) also predict the existence of the two mechanisms: abstraction through TS1, and insertion through TS2 and then TS3. At a collision energy of 2.0 eV, just 0.23% of trajectories into H_2 products react via path 2. Had it not been for the quantum interference, the insertion mechanisms would have passed unnoticed. However, interference can cause negligible contributions to exert large effects, because it sums the probability amplitudes and then squares the result to yield probabilities, rather than just adding the probabilities (*9*, *10*, *12*). Quantum interference reveals the presence of the CI at energies well below its energy on the PES. The phenomenon observed is analogous to the Aharonov-Bohm effect, and as in that case, it may occur far away from the CI. ■

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TOPOLOGICAL OPTICS

Twisted light on a chip

Compact devices provide new ways to generate and detect optical vortex beams

By **Li Ge**

A large-scale vortex is an extraordinary phenomenon to behold, be it a hurricane in the North Atlantic Ocean or the Great Red Spot on Jupiter. A vortex on a small scale is equally fascinating, especially when its quantum nature starts to emerge. Alexei Abrikosov won a Nobel Prize by introducing vortices in a phenomenological model to describe a new type of superconductor in 1950s (*1*), which turned out to be a feature of paired electrons in supercurrent. A very different type of vortex can be created for light (*2*). On pages 760 and 763 of this issue, Zhang *et al.* (*3*) and Ji *et al.* (*4*) demonstrate new ways to generate and detect such optical vortex beams on a tiny semiconductor chip.

Unlike dust, molecules, or electrons, photons do not have mass or charge and hence cannot be easily steered to move in a whirlpool fashion in open space. Nonetheless, one can imagine a bundle of tilted light rays that start simultaneously on a ring and end synchronously on another, some distance down the optical axis (see the figure). This twisted bundle gives a rough approximation of a Gaussian beam, and the "donut hole" at the optical axis is a direct consequence of the wave property of light. The polarization of light (the oscillation direction of its electric field) is spatially homogeneous in a simple beam and is often referred to as the spin angular momentum. Depending on whether the electric field oscillates along a straight line ("linear polarization") or a circle ("circular polarization"), the spin angular momentum takes the value of 0 or $\pm\hbar$, where $\hbar$ is the reduced Planck constant. If we go around a loop centered at the optical axis once, the electric field returns to its original value and the phase of its complex amplitude ($\mathbf{E}_\perp$) changes by an integer l times 2π. This requirement holds even for a loop much smaller than the wavelength, which is the scale on which $\mathbf{E}_\perp$ changes. Thus, the electric field must vanish near the optical axis unless $l = 0$.

l is proportional to the orbital angular momentum L of an optical vortex beam, which can only take a set of discretized values and is therefore said to be quantized—a concept at the heart of quantum mechanics. However, unlike the wave function that describes the probability amplitude of finding an electron in an atomic orbital, the aforementioned vector nature of light introduces another twist: The state of polarization in an optical beam is not necessarily homogeneous in space (*5*). Two examples of such vector vortex beams are polarized in the radial and azimuthal direction, respectively, each carrying an orbital angular momentum $l\hbar$ and no spin angular momentum. If they are mixed, a small fraction of the orbital angular momentum somehow appears to be transferred to the spin angular momentum (*6*), and neither of them is quantized anymore. This seemingly strange behavior can be understood by realizing that these two vector vortex beams are superpositions of two spin-orbital locked states (*7*) with equal weights. In one, the orbital and spin angular momentum are given by $(l - 1)\hbar$ and $\hbar$, respectively, and in the other by $(l + 1)\hbar$ and $-\hbar$, both with total angular momentum $J = l\hbar$. The mixture of two vector vortex beams then breaks this balance in general.

To generate and switch between such correlated states on-chip, Zhang *et al.* used a judiciously designed semiconductor optical microcavity (*8*, *9*) shaped in a ring with a radius of <4 µm. A clockwise lasing mode inside is scattered upward by the "gear teeth" on the inner surface of the ring and radiates into one correlated state with $J = -2\hbar$ and $L = -\hbar$, whereas a counterclockwise lasing mode scattered upward carries $J = 2\hbar$ and $L = \hbar$ instead because of the chiral symmetry of the ring cavity. Although there are several approaches to generating only a clockwise or counterclockwise mode in a microring laser (*10*, *11*), ultrafast and reliable switching (*12*) between them has been a challenge. The authors coupled the microlaser to a curved ancillary waveguide with two control arms, thereby realizing an imaginary gauge field first proposed in non-Hermitian quantum mechanics (*13*). By pumping either control arm, the corresponding correlated state was produced with high purity. Together with their superposition, as well as an optional on-chip spin-orbital conversion through a radial polarizer, a range of switchable L values between $-2\hbar$ and $2\hbar$ was demonstrated at a single telecommunication wavelength, as verified by their distinct pitchfork patterns in

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laterally shifted self-interference (see the figure for the $L = \hbar$ beam).

A compact source of optical vortex beams requires a minute detector. Ji *et al.* realized a previously unappreciated photogalvanic effect (*14*) to enable direct on-chip electrical readout of orbital angular momentum in an optical vortex beam. This effect bears a similarity to the photon drag effect (*15*), where the linear momentum of absorbed photons is transferred to charge carriers. The difference between the two effects can be readily understood from the twisted bundle of rays: The demonstrated photogalvanic effect would vanish if each ray were independent, whereas the photon drag effect would be unaffected. The helical phase gradient of the optical beam leads to a photocurrent proportional to L, which is governed by the fourth-order conductivity tensor. Ji *et al.* fabricated electrodes of various shapes on tungsten ditelluride, a room-temperature Weyl semimetal with broken inversion symmetry, for use as photocurrent detectors. They found that the photocurrent displayed steplike changes with L, from which the contribution due to spin angular momentum was also eliminated reliably.

These two demonstrations provide a robust platform from which to scale down the footprint of optical vortex laser generation and detection, which so far rely largely on traditional bulk and fiber optical elements (*2*, *5*). Switching the angular momentum directly from the source opens new opportunities in signal multiplexing and modulation in telecommunications. A potential issue is the orthogonality of multiple signal channels: Switching from a spin-orbital correlated state to a vector vortex beam polarized in the radial or azimuthal direction is similar to switching from circular polarization to linear polarization. Whether single photons with orbital angular momentum can be generated and measured on this platform awaits further investigation of the possibilities for its application in quantum information processing. ■

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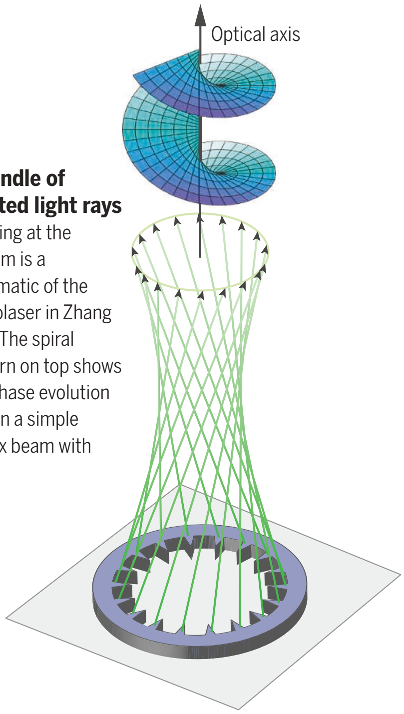
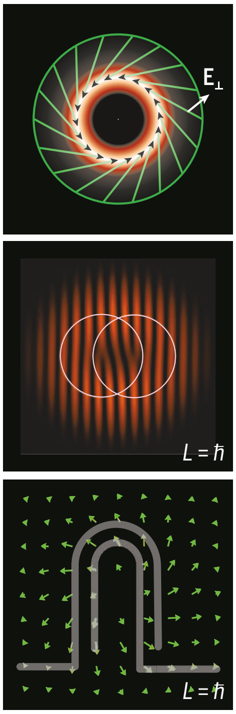
On-chip generation and detection of twisted light

Zhang *et al.* and Ji *et al.* developed chip-scale methods to generate and detect optical vortex beams.



A bundle of twisted light rays
The ring at the bottom is a schematic of the microlaser in Zhang *et al.* The spiral pattern on top shows the phase evolution of $\mathbf{E}_\perp$ in a simple vortex beam with $L = \hbar$.



View from the optical axis at half height of the twisted bundle
The donut-shaped beam pattern and the direction of the transverse electric field are superposed.

Pitchforks formed in self-interference
The two circles illustrate the lateral shift of the same vortex beam.

Vortex detection
Photocurrent (green arrows) is generated by the helical phase of an optical vortex beam and the collecting electrodes used by Ji *et al.*

GEOPHYSICS

Seismicity from the deep magma system

Deep seismicity may reflect magma cooling beneath volcanoes

By **Robin S. Matoza**

A systematic scan of seismic waveform archives on the Island of Hawai‘i has revealed subtle but persistent near-periodic pulses originating within the deep magma plumbing system of Mauna Kea, a dormant volcano that last erupted ~4500 years ago. On page 775 of this issue, Wech *et al.* (*1*) report the detection of over a million of the deep (22 to 25 km below sea level) long-period seismic events, which have been occurring continuously and repetitively, often with precise regularity (every ~7 to 12 min), for at least 18 years. This discovery offers new views into the origin of this mysterious type of deep volcanic seismicity.

Seismic data form the backbone of most volcano monitoring networks and play a critical role in understanding how volcanoes work. Volcanic seismicity includes volcano-tectonic (VT) earthquakes (ordinary brittle-failure earthquakes driven by magmatic stresses) and long-period [(LP), 0.5 to 5 Hz] seismicity (volcanic seismicity that is thought to actively involve a fluid in the source mechanism) (*2*). LP seismicity includes individual transient LP events and sustained volcanic tremor signals. LP seismicity at shallow depth (<3 km) in a volcanic edifice is commonly explained by the excitation and resonance of fluid-filled cracks associated with magmatic-hydrothermal interactions or magmatic degassing and is a characteristic signature of unrest and eruption (*3*). Precise regularity in sustained sequences of shallow LP seismicity has been documented at numerous volcanoes worldwide (*2*).

In the roots of volcanic systems below this shallow activity, seismicity extends down to mantle depths (to ~60 km), but linking seismicity to magma pathways is not straight-

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Science

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