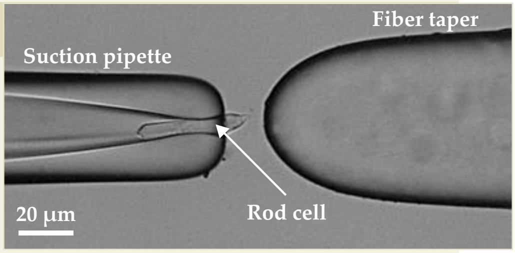
Frog eyes show prowess as quantum sensors



The human eye, once it acclimates to darkness, can detect bursts of light containing as few as a hundred photons. That ability suggests that rod cells—the retinal photoreceptors that specialize in night vision—can detect single quanta of light: Even after accounting for focusing, it's unlikely that any two photons from so faint a flash would arrive at the same one of the roughly 120 million rods that line the inner eye.

Studies dating back to the 1940s have generated compelling, albeit circumstantial, evidence in favor of that proposition. Statistical analyses of human behavioral data suggest that only about 10% of the photons in a just-visible flash of light contribute to retinal stimulation.[1] The rest are scattered within the eye or go unabsorbed by the retina's photoreceptors, which makes it even less likely that a single rod would register multiple-photon hits. In other experiments, rods irradiated with few-photon pulses generated electrical signals of quantized amplitude.[2] Presumably, the smallest signals correspond to single-photon stimulations. The next largest, roughly twice as big, are thought to herald two-photon stimulations, and so forth.

Researchers led by Leonid Krivitsky at the Agency for Science, Technology and Research in Singapore have now probed the limits of rod sensitivity in a more direct fashion—by firing photons one by one at rods plucked from the eyes of African clawed frogs.[3] The figure shows the group's experimental setup. Photons are delivered via an optical fiber to a rod held in a pipette, where electrodes record spikes in the cell's transmembrane potential.

Similar experiments have been performed using lamps or LEDs dimmed to deliver pulses with a mean photon number close to one. Such pulses, however, are described by a Poisson distribution; although many of them may carry one photon, others will carry two or more, and a large share will carry none at all. One can't say for sure how many photons contribute to a particular cell response and, as a result, one can't directly calculate the cell's single-photon detection efficiency.

To generate pulses containing precisely one photon, Krivitsky and company exploited a process known as parametric down conversion, in which a crystal converts one high-energy photon into a pair of low-energy ones. (See the article by Alan Migdall, Physics Today, January 1999, page 41.) In their particular implementation, the researchers shine a UV laser into a barium borate crystal, which occasionally spits out a pair of visible photons. One of the photons is steered to an avalanche photodiode, where its detection triggers an acousto-optical modulator to divert the second photon into the fiber that leads to the rod.

"The thing about an experiment like this," says Krivitsky, "is that time works against you." After harvesting a rod from its amphibian host, he explains, there's just a one- to two-hour window in which to work before the cell loses viability. Meanwhile, to allow the cell adequate recovery time between spikes, pulses must be delivered at a rate of no more than about 10 per minute. In the pursuit of a statistically robust data set, every photon is precious. The optical fiber's shape helps ensure that photons find their target: Its rounded tip acts as a lens that focuses outgoing light onto a spot 4 μm across, to match the diameter of the rod.

The team's results, amassed with 10 rods harvested from 10 different specimens, indicate that an impinging photon has a nearly one in three chance of eliciting a spike. Previous experiments using conventional light pulses to stimulate rods of a related species, the cane toad, found detection rates of just 6%. The new estimate is roughly in line with the range predicted for human rods.

Indeed, rods appear to detect single photons almost as reliably as do many commercially available sensors, including some avalanche photodiodes. The rod response, however, is much more sluggish. Each spike is the product of a regulatory cascade that's thought to start with the photoisomerization of a lone pigment molecule and culminate, nearly two seconds later, with the closing of several hundred ion channels. For Nicolas Gisin, a quantum optician at the University of Geneva, that raises an intriguing question: How is it that even in dim settings we can react to visual cues almost instantly? "As far as I know, there's still no good answer," he says. "But the information processing that's involved must be remarkable."

Ashley G. Smart

References

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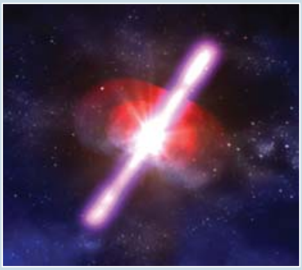
physics update

These items, with supplementary material, first appeared at http://www.physicstoday.org.

Circularly polarized light from a gamma-ray burst. Gamma-ray bursts (GRBs) are the most violent explosions in the universe. Most of them are likely powered by jets of relativistic particles that are launched from dying stars as they collapse into a compact object such as a black hole. They are named for their initial blast of high-energy radiation, but GRBs can glow for days, emitting radiation across the electromagnetic spectrum. Studies of the linear polarization of GRB light provide information about the magnetic field in the jet and help clarify jet geometry. Now, a collaboration led by Klaas Wiersema of the University of Leicester in the UK reports having observed circularly polarized optical light in the radiation of a GRB detected on 24 October 2012. The strength of the signal, measured a few hours subsequent to the initial burst, in the afterglow phase, was orders of magnitude above what simple models predict. Scattering from dust can convert linearly polarized light into the circularly polarized variety, and the Wiersema team considered that possibility as a source for their signal. They concluded, however, that the scattering processes capable of generating the circularly polarized light they measured would also affect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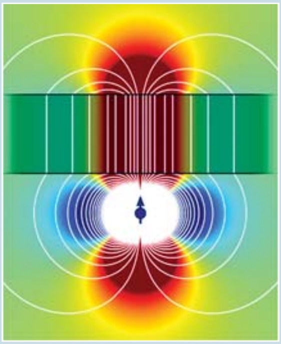
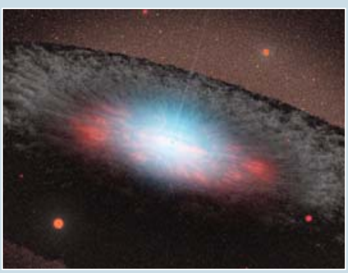
linearly polarized light in a manner inconsistent with their data. Models of GRBs generally assume that the electrons in the shocked ambient material responsible for the afterglow have velocities that are isotropic with respect to local magnetic field lines. Theorists recognize that one way to get circularly polarized light in a GRB is to relax that assumption. But they have yet to craft a convincing model that incorporates anisotropy. (K. Wiersema et al., *Nature* **509**, 201, 2014.) —SKB

The magnetic hose. A guide that routes static magnetic fields as easily as fiber optics carry light could one day see applications as diverse as stepping up voltage in a transformer or manipulating a tiny quantum system. Now researchers led by Alvar Sanchez of the Autonomous University of Barcelona have taken the first step toward developing that routing technology, with a device they call the magnetic hose. The hose works because it is made from a material that has an anisotropic magnetic permeability and thus responds differently to magnetic fields entering it from different directions.



The figure illustrates the theory for the extreme case of an infinite slab with infinite permeability in the vertical (z) direction and zero permeability in the orthogonal directions. Within the material, the field (white lines) is totally vertical. As a result, the dipole field (whose z component is illustrated by the colors) is faithfully transmitted across the slab. Sanchez and company fabricated their finite-sized, finite-permeability hose by surrounding a cylindrical ferromagnet with a coaxial superconducting shell. The ferromagnetic core gives the hose a large permeability in the axial direction, analogous to the z direction in the figure, whereas the field-expelling superconductor enforces nearly zero permeability in the radial directions. To assess their device's performance, the researchers placed a current loop slightly below the hose and measured the dipole field slightly above it. For each of two different hose lengths (6 cm and 14 cm), they found the measured field was at least twice as great as for the ferromagnetic core alone. In theory, additional alternating shells of ferromagnet and superconductor could improve the hose's ability to transmit magnetic fields. (C. Navau et al., *Phys. Rev. Lett.*, in press.) —SKB

Why do active galactic nuclei differ? In some galaxies, including our own, the black hole sits inconspicuously in the middle. But in others, the black hole is orbited by a thick toroidal disk of hot gas. As material in the disk spirals toward the black hole's event horizon, the disk's inner region becomes so agitated and hot that it radiates copiously (see the accompanying artist's impression). Such systems are known as active galactic nuclei, of which there are two broad classes.



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Type 1 AGNs have broad emission lines characteristic of hot, fast-moving matter. Type 2 AGNs have narrow lines characteristic of cool, slow-moving matter. Given that a thick torus shrouds the AGN engine, the two AGN types could conceivably differ only by viewing angle: Type 1s afford a face-on view of the hot, swirling inner disk; type 2s, an obscured view. Known as AGN unification, that appealing explanation can account for some of the differences between the two AGN types, but not all of them. Now Beatriz Villarroel and her thesis adviser Andreas Korn of Uppsala University in Sweden have shown that another factor is at play. Using data from the Sloan Digital Sky Survey, Villarroel and Korn looked at the neighboring galaxies of a sample of 11 334 type 1 and 53 416 type 2 AGNs. If viewing angle were the sole discriminant, the properties of galaxies in an AGN's vicinity would have no bearing on its type. But that's not the case. Compared with the neighbors of type 1s, the neighbors of type 2s are significantly bluer and seem to be making more stars. Although viewing angle does influence an AGN's outward appearance, Villarroel and Korn's findings indicate that type 1s and type 2s are intrinsically different, perhaps because of their collision histories. (B. Villarroel, A. J. Korn, *Nat. Phys.* **10**, 417, 2014.) —CD

One mystery of magnetic plasma confinement solved. The fusion of nuclei generates prodigious amounts of energy, as in the Sun's core. Harnessing that energy is the primary goal of researchers who work on tokamaks—large toroidal machines in which a plasma can be confined by magnetic fields and held at high enough temperatures and densities to engender fusion. (See the article by Donald Batchelor in PHYSICS TODAY, February 2005, page 35.) Yet the goal remains elusive, in no small part due to myriad instabilities that arise on a multitude of length and time scales, degrading the magnetic confinement of the hot plasmas.

In the 1990s researchers discovered that sheared rotation of the plasma and a specific plasma current profile could generate so-called internal transport barriers (ITBs) that inhibit plasma transport across a magnetic surface within a tokamak. The nonlinear, multiscale physics at the heart of ITBs, however, proved to be difficult to unravel. In particular, still unsolved was the mystery of precisely why the ion energy transport was suppressed with ITBs but the particle and momentum transport of the ions was not. Now Gary Staebler and the tokamak team at the DIII-D National Fusion Facility (shown here) operated by General Atomics in San Diego, California, have demonstrated that instabilities at intermediate length scales near the ion gyro-radius (about a millimeter) survive the strong rotation shear and provide the electron energy and momentum transport across the ITB. Using a multiscale quasi-linear transport model, the researchers were able to accurately predict the ion and electron densities and temperatures as well as the rotation of a real ITB experiment at the DIII-D. The upshot is that gyrokinetic turbulence theory works, even in ITBs. (G. M. Staebler et al., *Phys. Plasmas* **21**, 055902, 2014.) —SGB ■