

flux spectrum shown in figure 2. What's plotted is, in effect, the flux through the local plane whose orientation maximizes the flux. Because of the near-90° spiraling, that plane generally includes the field line.

In its brief visits to the SAA, PAMELA recorded no trapped $\bar{p}$ s with kinetic energy above 1 GeV. Beyond that energy, theoretical models expect the population to fall precipitously, reflecting the increasing difficulty of keeping an energetic particle trapped. The curve in figure 2 shows the expected $\bar{p}$ flux spectrum based on a model by theorist Richard Selesnick and coworkers.³ The model expectation exceeds the measured flux out to 1 GeV by about a factor of 10. "That's considerably bigger than our estimated 10% systematic uncertainty [not included in the plotted statistical error bars]," says team member Francesco Cafagna (National Institute of Nuclear Physics, Bari). "Probably the four-year-old model just needs some fine tuning."

Much starker is the contrast in figure 2 between the flux of trapped $\bar{p}$ s and the flux of cosmic-ray $\bar{p}$ s, also measured by PAMELA. In the energy range over which both have now been measured, the former dwarfs the latter by three orders of magnitude.

When the public press first reported

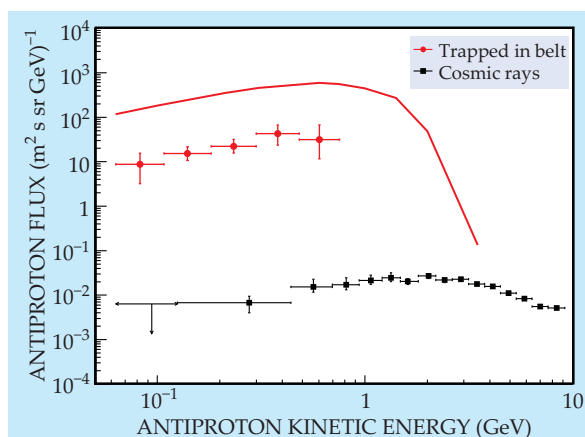


Figure 2. The flux spectrum of antiprotons trapped in Earth's inner Van Allen belt is compared with a prediction (solid curve) based on a theoretical model³ and with the much smaller flux of cosmic-ray antiprotons at energies below 1 GeV. Both spectra were measured by the PAMELA orbiting spectrometer. (Adapted from ref. 2.)

the discovery of antimatter trapped so close by, there was much loose talk that it might one day serve as a fuel source for spacecraft. But any plausible integration of the PAMELA findings over the entire inner Van Allen belt yields a total $\bar{p}$ mass of only a few nanograms. Its complete annihilation would provide about as much energy as eating a banana or two.

So, aside from the discovery and its gratifying confirmation of a decades-old expectation, what's the use of studying the trapped $\bar{p}$ s? The detailed radiation perils of traversing the inner Van Allen belt are already known well enough from the trapped-proton data.

But because of the roundabout way trappable $\bar{p}$ s have to be created, they provide a unique test of models of cosmic-ray transport in the atmosphere and the radiation belts. "The more you learn about local effects," says Cafagna, "the better you can disentangle them from galactic phenomena."

Bertram Schwarzschild

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Microfluidic circuits harvest mechanical energy

Embedded in a pair of shoes, circuits composed of a train of conductive droplets could generate a few watts of power—enough to charge a cell phone from a casual stroll.

Imagine a drop of water on a solid, pulled up into a ball by surface tension. The simple application of a voltage polarizes the solid surface and prompts the drop to spread out to minimize the system's free energy; the greater the voltage the greater the spread. In essence, the liquid-solid interface behaves like a capacitor, and the change in wettability arises from the extra electrostatic energy stored at the charged surface, as outlined in figure 1.

The phenomenon, known as electrowetting, has its roots in Gabriel Lippmann's 1875 experiments on voltage-induced variations in the capillary action of mercury in contact with an electrolytic fluid. But only recently has electrowetting found wide applicability,¹ largely thanks to CNRS scientist Bruno Berge's realization in the early 1990s that a thin insulating dielectric placed between the electrode and electrolyte would stabilize the effect by preventing oxidation or other electrochemical reactions at the interface.

In the past decade, researchers exploiting the electrowetting effect have developed liquid lenses with voltage-tunable focal lengths for miniature cameras, electronic screens whose pixels wet and dewet on command to alter color or contrast, and other applications. In microfluidics, if the electric field is applied nonuniformly, the gradient in surface energy along a channel

can be used to control droplet flow through complex circuits without the need for pumps, mixers, or valves.

Tom Krupenkin and Ashley Taylor at the University of Wisconsin-Madison have now developed an approach that runs the electrowetting process in reverse and converts the mechanical energy of liquid motion into electrical energy.² Figure 2 illus-

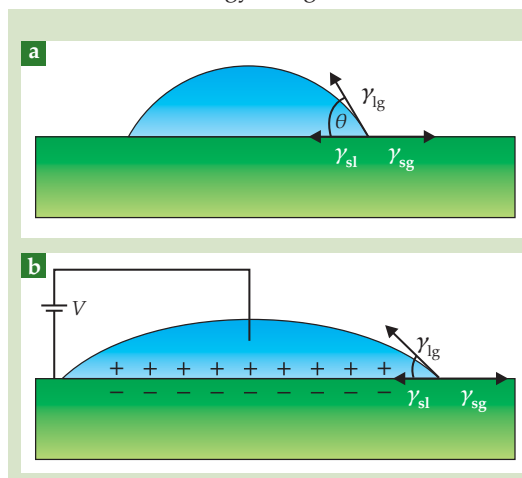
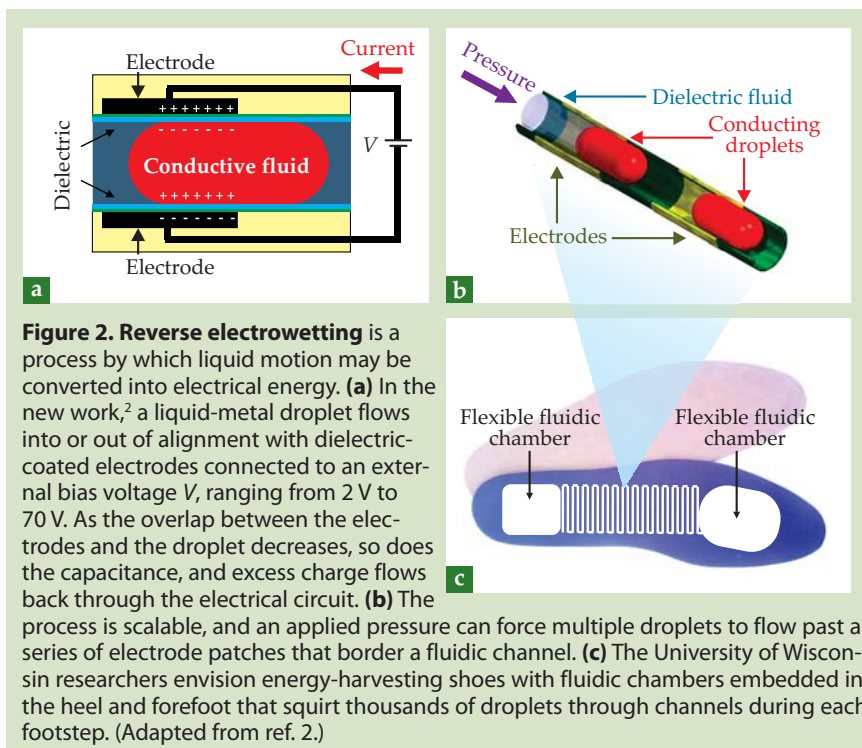


Figure 1. (a) When a drop wets a surface, each interface experiences a surface tension. At equilibrium, the horizontal components of liquid-gas γ_{lg} , solid-liquid γ_{sl} , and solid-gas γ_{sg} tensions must balance, which determines the contact angle θ . (b) When a voltage V is applied between the drop and solid surface, the interface behaves like a parallel-plate capacitor whose capacitance C lowers the solid-liquid interfacial energy by $CV^2/2$, which lowers the contact angle. (Adapted from ref. 3.)



trates the concept: A conductive droplet and two dielectric-coated electrodes are connected by an electrical circuit that provides a constant bias voltage. As the droplet's shape or position changes—when it's squeezed between vibrating plates, sheared along sliding ones, or, as in the figure, slid past fixed ones bordering a fluidic channel—the amount of charge stored at the liquid–solid interface changes.

The droplet thus acts like a variable capacitor. As the areal overlap at the liquid–solid interface decreases, so does its capacitance, and excess charge flows back through the electrical circuit. In the case of a microfluidic channel in which a train of droplets is squirted through one end or the other, the flow of droplets into and out of alignment with the electrodes drives an alternating current and can power an external load. The power is proportional to the change in capacitance and to the square of the bias voltage across the interface.

Energy-harvesting schemes based on variable capacitors are not new, but they've historically been limited by the mechanical difficulty of machining macroscopically large electrodes fine enough to nearly close a microscopic gap between them. Capacitance scales directly with electrode area but inversely with gap distance, so the thinner the better, barring dielectric breakdown. "Because the dielectric gap in reverse electrowetting is a solid layer," says University of Twente physicist Frieder Mugele, "it can be grown nanometers thin and yet remain me-

chanically stable." As droplets then flow sideways along the dielectric, they generate huge variations in capacitance on the scale of 20 nF/cm². "It's a simple, clever idea, and frankly one I wish I'd had myself."

Power walking

In one implementation, Krupenkin and Taylor fashioned patches of tantalum oxide-coated electrodes along a fluidic channel a millimeter or so wide. Using a resistor as the load, they measured a few milliwatts from the channel containing up to 22 droplets of mercury. But the power scales nonlinearly with the droplet number. From their model of the process, the researchers calculate that average powers of 1 W or more could easily be generated (at a bias of at least 20 V, admittedly) in a fluidic device with 1000 droplets.

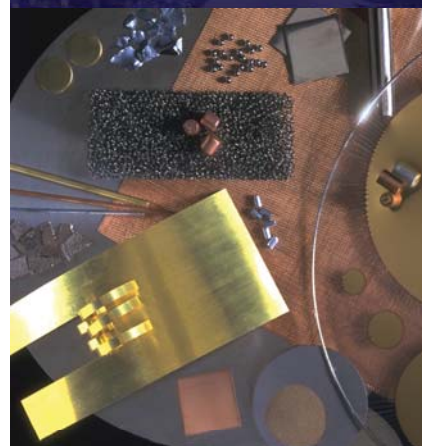
The devices can be small and compact. A 4-m-long train of 1000 droplets, each 1 mm long and spaced by 1 mm, would occupy about 40 cm², less than a quarter of the area of a typical human footprint. The compression required to squirt the roughly 4-ml volume through channels in a pair of shoes, for example, is about 2 mm—well below the level that might affect a person's gait.

Conductive droplets don't behave like ideal capacitors, though, and the envisioned energy harvester has limits. For nanometer-thick dielectric films, even a few volts can generate strong electric fields on the scale of 10⁶ V/cm and trap charges in the dielectric, which inhibits the electrowetting effect.

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Applying a coat of fluoropolymer to the Ta_2O_5 dielectric ameliorates the problem, the researchers found, but cannot prevent it.

Nonetheless, Krupenkin and Taylor remain sanguine about embedding their circuits in a pair of shoes to drive mobile electronics such as a cell phone, music player, or emergency flashlight. Fortunately, mercury isn't the only metal that is liquid at room temperature; galinstan, a nontoxic, liquid-metal

alloy of gallium, indium, and tin, has proven equally effective when sealed off in closed channels to avoid oxidation. The two researchers don't expect the shoes to replace batteries, only to keep them charged and to dramatically extend their lifetime. (For more on the challenges associated with rechargeable batteries, see the article by Héctor Abruña, Yasuyuki Kiya, and Jay Henderson in *PHYSICS TODAY*, December 2008, page 43.)

So far, they have patented the idea, talked with the US military, and founded a company (InStep NanoPower) but have not yet commercialized the technology.

Mark Wilson

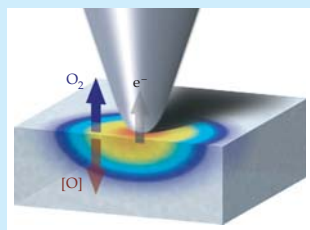
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physics update

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

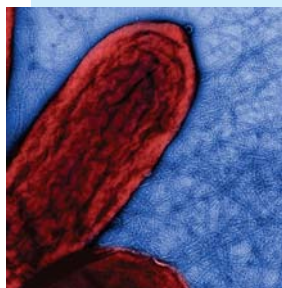
Nanoscale electrochemistry. Although rechargeable batteries and fuel cells have been increasingly considered for or used in mobile electronic devices and electric vehicles, they have not been adopted for large-scale energy-storage and power generation primarily because their energy and power densities are still orders of magnitude below hydrocarbon fuels. Those densities



can be greatly improved in metal-air batteries and fuel cells that tap an unlimited supply of environmental oxygen. Studies have shown that the reduction and formation of molecular oxygen in an electrochemical process play a significant role in limiting

the efficiencies of those technologies, but insight into the dynamics of those reactions has been hindered by an inability to probe and model them on the nanoscale. Now, researchers from the US, Germany, and Ukraine, led by Sergei Kalinin at Oak Ridge National Laboratory, have employed a scanning probe microscope to map local electrochemical activity on a surface by tracing the appearance, disappearance, and diffusion of oxygen vacancies. As shown in the sketch, a platinum-coated cantilever tip (which doubles as a catalyst) applies a voltage bias to the surface and generates or annihilates oxygen vacancies; the false colors represent the concentration of reduced oxygen. The associated volume change produces an electrochemical strain that is detected by the microscope. Information from the resulting maps may lead to batteries and fuel cells whose mesoscopic architecture is designed to optimize the oxygen-reaction processes. (A. Kumar et al., *Nat. Chem.* **3**, 707, 2011.) —JNAM

Metal-like microbial nanowires. Although most bacteria are electrical insulators, some do support electric currents. Debates remain, however, over the nature of that transport (see *PHYSICS*

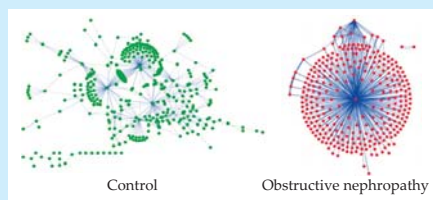


TODAY, December 2010, page 18). New work by microbiologist Derek Lovley, physicist Mark Tuominen, and colleagues at the University of Massachusetts Amherst shows that the anaerobic bacterium *Geobacter sulfurreducens* can conduct along filaments attached to the cell membrane. Composed of the protein pilin, the filaments—only 3–5 nm wide and up to tens of microns

long—have metal-like properties akin to those of synthetic organic conductors. Furthermore, the filaments form extended

networks, like the one seen here in dark blue surrounding a bacterium 0.5 μm wide, that can conduct over centimeter distances. The researchers studied the nanowire networks by growing films of living *G. sulfurreducens* on top of two electrodes separated by a 50- μm gap. The biofilms had a conductivity of 5 mS cm^{-1} , comparable to that of manmade polymer nanostructures, and exhibited many hallmarks of metallic behavior. In a transistor configuration, a nearby gate electrode could modulate the film's conductivity by a factor of 100. At moderate temperatures, the conductivity showed an exponential temperature dependence reminiscent of quasi-one-dimensional organic metals. Disorder effects began to dominate at low temperatures, which suggests that appropriate processing to remove network defects could improve the conductivity for potential applications. Microbial nanowires, say the researchers, could open the door to a range of conducting nanomaterials that are naturally occurring, nontoxic, and inexpensive to produce, for such uses as environmental cleanup, biosensors, and power applications. (N. S. Malvankar et al., *Nat. Nano.*, in press, doi:10.1038/nnano.2011.119.) —RJR

Network analysis diagnoses kidney disease. Obstructive nephropathy (ON) is the most common kidney disease among children. Sufferers have a blockage of the urinary tract, which forces urine back into the kidney. If unrecognized and unchecked, the ensuing damage shuts down the organ. In principle, kidney function and malfunction are reflected in the metabolites that pass through the kidney and the regulators that control the metabolites' consumption and production. But of the myriad species of metabolites and regulators, which ones presage ON? To answer that question, Massimiliano Zanin and Stefano Boccaletti of the Technical University of Madrid turned



to network theory. Their starting point was a database of 852 metabolites and 834 regulators (microRNAs) drawn from 10 ON patients and a 10-member control group. Levels of metabolites and regulators varied within each group. Still, it proved possible to construct for each metabolite (or regulator) a network that embodied how far every other metabolite (or regulator) deviated from its statistically expected correlation. As the examples in the figure show, control group networks had amorphous topologies, whereas ON networks had star-like topologies centered on the most abnormal metabolite or regulator. Thanks to their simplicity, ON networks are more "efficient" than control networks—that is, the paths between all their node pairs are shorter on average. That difference, Zanin and Boccaletti propose, could underlie an early ON diagnostic. (M. Zanin, S. Boccaletti, *Chaos* **21**, 033103, 2011.) —CD