ent flavors of neutrinos is well understood, the ratio of muon to electron neutrinos generated in the atmosphere can be predicted with confidence. The ratio detected by Super-Kamiokande and several other experiments, however, differs from these predictions.

The difference, known as the atmospheric neutrino anomaly, suggests that one or both of the neutrinos are oscillating and thus changing the ratio. But Super-Kamiokande can go a step further by tracking the direction of the incoming neutrinos. In particular, the Super-Kamiokande team compared neutrinos coming down from the sky with those coming upward through Earth. Because the cosmic rays and their resulting neutrinos rain down equally from all directions, the ratio should be 1. But if oscillation can occur, the neutrinos coming the 13,000 kilometers from Earth's far side have more time to oscillate than the neutrinos traveling only 20 kilometers down from above.

For electron neutrinos, Super-Kamiokande caught equal numbers going up and coming down. But for muon neutrinos there was a big difference. In 535 days of operations, Super-Kamiokande counted 256 downward muon neutrinos and just 139 upward ones. The large number of observed neutrinos and the magnitude of the difference reduces the chances of the finding being a statistical fluke, say team members. Taken together, the data indicate that the muon neutrinos are oscillating, perhaps to tau neutrinos, which the detector cannot pick up. "From these data we conclude that we have strong evidence for muon neutrino oscillations," says Takaaki Kajita, an ICRR physicist who presented the Super-Kamiokande results.

Despite the awe that greeted the presentation—Bahcall called it "one of the most thrilling moments of my life"—the results were anything but surprising. "We have been releasing data all along," says Henry Sobel, a University of California, Irvine, physicist who heads the American side of the collaboration. "And we started seeing [evidence of oscillation] from the first data set." Late this spring, the group decided that the latest data had put them over the top. "Everyone was convinced we had done everything possible to find artifacts or misunderstandings," says Yoji Totsuka, ICRR director and head of the collaboration.

Now neutrino experts will begin pondering new questions. Measuring oscillations can only yield the difference between the masses of the two flavors being measured, not their absolute mass. In this case, the mass difference is about 0.07 electron volt, or about one 10-millionth of the mass of the electron. That figure serves as a lower limit for neutrino mass.

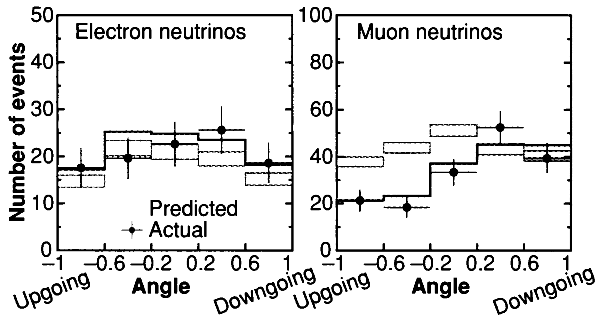
The uncertainty also leaves unresolved one fierce cosmological debate—whether neutrinos make up a significant part of the universe's dark matter, the mass theorists believe must be present for the universe to exist as we know it but which can't be accounted for by the observable stars and planets. John Learned, a Super-Kamiokande collaborator at the University of Hawaii, Manoa, says that the result implies that neutrinos are a significant fraction of the dark matter, but David Caldwell of the University of California, Santa Barbara, says the Super-Kamiokande evidence is irrelevant because that lower limit is "too low to be significant."

Theorists have other issues to address. Paul Langacker, a physicist at the University of Pennsylvania, says, "Standard Model theories will have to be extended" to accommodate a neutrino with mass. Others believe that the revisions could be major. Barry Barish of the California Institute of Technology in Pasadena says the massive neutrino "is the first empirical evidence providing a clue for what is beyond the Standard Model." In particular, a massive neutrino is one of the cornerstones of Grand Unified Theories, which seek to provide a unified explanation for all known particles and forces.

Experimentalists still have lots to do as well, including verifying the Super-Kamiokande results. Several groups are now readying long-baseline experiments in which a stream of neutrinos generated by an accelerator is aimed at a detector hundreds of kilometers away. Such experiments promise greater detail on oscillations by actually counting the number of neutrinos at the source, instead of relying on theory, as the atmospheric neutrino experiments do. But their range and energy levels don't fit the parameters; Harvard's Glashow gives them only a 50–50 chance of confirming the Super-Kamiokande findings.

More data will certainly be necessary to stitch the results into a consistent picture of neutrino masses. Whatever the outcome, this ephemeral particle seems likely to have a weighty impact on physics.

–Dennis Normile



Amassing evidence. The number of muon neutrinos detected coming up through Earth falls short of what theory predicts *(right)*, which suggests that they are transforming into some undetected neutrino type. Electron neutrinos follow the expected curve *(left)*.

SOURCE: SUPER-KAMIOKANDE COLLABORATION

COMBINATORIAL CHEMISTRY

The Fast Way to a Better Fuel Cell

Combinatorial chemistry—the shotgun approach to chemical discovery whereby researchers synthesize and test hundreds or thousands of different compounds simultaneously—is already revolutionizing the discovery of new drugs. Researchers are working to apply the strategy to finding hot new materials, such as catalysts, as well. But in many cases, testing hundreds or thousands of new catalysts at once can be a major obstacle. Now a team at Pennsylvania State University, University Park, and the Illinois Institute of Technology (IIT) in Chicago has found a way around this bottleneck, coming up with a method for quickly selecting the better catalysts for everything from fuel cells to batteries.

The technique, which signals the presence of an effective catalyst with a fluorescent glow, has already yielded a concrete result, as the researchers, led by Penn State chemist Tom Mallouk and IIT chemical engineer Eugene Smotkin, report on page 1735. They used it to discover a new catalyst for converting methanol to electricity in fuel cells—devices that are being hotly pursued by companies around the world as a clean alternative to combustion engines. The catalyst isn't ideal, Mallouk and others note: Among its ingredients are osmium—potentially toxic—and iridium, which is prohibitively expensive, along with platinum and ruthenium. Nevertheless, its discovery shows that in the search for better catalysts, the brute strength of combinatorial chemistry "is definitely worth pursuing," says Tom Fuller, a methanol fuel-cell expert at International Fuel Cells in South Windsor, Connecticut.

Current fuel-cell catalysts consist of an equal mix of platinum and ruthenium, which, with the help of a small electrical voltage, break down methanol into carbon dioxide, protons, and electrons. The electrons are routed through a wire to power a car or do other work and are eventually channeled to another electrode in the cell, where they meet up with the mobile protons. But these catalysts are inefficient, wasting about 25% of the energy stored in the fuel as heat instead of converting it to electricity. Researchers have searched for years to find an improved mixture of metals. Most of these efforts have concentrated on various mixtures of two metals or occasionally three, but few have tried four or more because so many different combinations are possible. "It gets very laborious to try to make and test them all one at a time," says Fuller.

To speed up the search with combinatorial chemistry, Mallouk and his Penn State colleagues took a hacksaw to a commercial inkjet printer and modified the machine to spray droplets of different metal salts instead of ink. They then used a computer to control the spraying of the salts, in the end creating an array of dots, varying both the component salts and their relative concentrations. Treating the dots with a strong reducing agent converted the salts to patches of metal alloy, each of which acted as a catalyst.

One way to pick out the best catalyst from such an array of candidates is to expose them to their target compound and detect the heat given off during the reaction. But fast-reacting catalysts can produce heat even when they make unwanted byproducts. So the Penn State researchers took a new approach: They simply spiked their array—which sits in an aqueous bath containing methanol—with a compound called nickel PTP, which fluoresces a faint blue in the presence of protons. To activate the catalysts, the researchers applied a small voltage across the array, sat back, and watched as their best catalysts lit up.

The Penn State team passed along their brightest prospects to their IIT colleagues, who made electrodes from the material and incorporated them into working fuel cells. They found that the best such catalyst works about 40% better than a straight platinum-ruthenium mix under simulated real-world conditions. Mallouk, Fuller, and others caution that this improvement may not be enough to justify using the more costly metals. But the promising results of this first attempt to use combinatorial chemistry suggest that there may be even better catalysts out there just waiting to be discovered.

–Robert F. Service

POLYMER ELECTRONICS

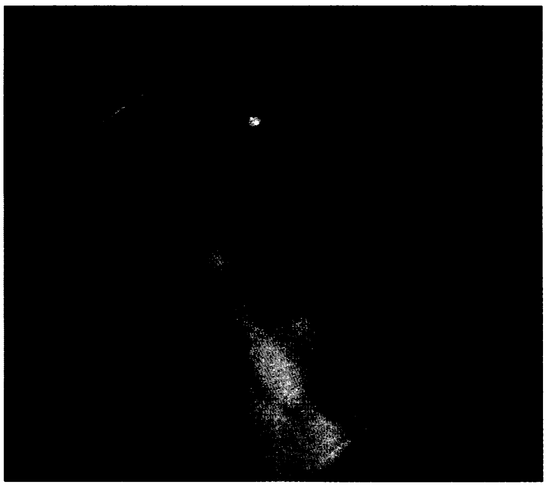
Transistors and Diodes Link and Light Up

Car bumpers, coffee mugs, computer casings: It seems that just about everything is made out of plastic these days. Researchers have even created plastic electronics, such as polymer-based transistors and glowing diodes. Now, separate teams of researchers in the United States and United Kingdom have managed to integrate these two types of devices for the first time, opening the way to lightweight, flexible displays made out of material not too different from garbage bags. Down the road, such displays could challenge conventional televisions and laptop displays and open up entirely new uses such as large-area illuminated signs that can be rolled up and carted away.

The new pairing between organic electronics and lights "is a breakthrough that the field of organic displays has been looking for," says Yang Yang, an organic-display expert at the University of California, Los Angeles. The advance, made possible by new polymers that carry higher currents, allows researchers to use simple, low-cost fabrication methods such as screen printing and inkjet printing to lay down all the different materials needed to create displays, says Yang. "It will be very exciting to see what you can do with all-organic systems," says James Sturm, an organic-display expert at Princeton University.

The prospect of all-organic displays has been tantalizing researchers for several years. Each point of light on such a display is a single light-emitting diode (LED) powered by an electric current, which is switched on and off by a transistor. The problem is that although organic LEDs typically need a rushing stream of current to shine, most organic transistors only put out a trickle. As a result, researchers have been forced to stick with conventional silicon-based transistors to drive their organic LEDs and so have lost some of the key advantages of plastics: flexibility, low cost, and low weight.

New hope for fully organic displays began to shine last year, when researchers at Lucent Technologies' Bell Laboratories in Murray Hill, New Jersey, and at Pennsylvania State University, University Park, came up with a new breed of high-current organic semiconductors. The two teams aiming to make all-organic displays, one at Bell Labs and one at Cambridge University, both settled on one of these new organics, a chainlike polymer known as regioregular poly(hexylthiophene). The polymer consists of a series of linked carbon and sulfur-based rings, with hydrocarbon chains dangling off each ring. When laid down in a solution, the chains and rings of different molecules prefer to associate with their own kind, and so the polymer assembles into alternating sheets of chains and rings. Current flows along the sheets of rings, and the close proximity of the rings in different molecules allows charges to jump freely from one molecule to the next. "This isn't perfect crystalline order, but it seems to be enough to boost the mobility of the electrical charges," says Cambridge physicist Henning Sirringhaus.



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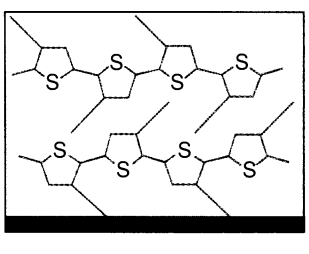

SIRRINGHAUS ET AL.

Bending light. Organic LED atop a thin silicon transistor. By replacing silicon with polymer *(left)*, new devices could be even more flexible.

On page 1741 of this issue, Sirringhaus and his Cambridge colleagues Nir Tessler and Richard Friend report fashioning this polymer into an organic transistor and using it to drive a conventional polymer-based LED built directly on top. Meanwhile, the Bell team, led by physicists Ananth Dodabalapur and Zhenan Bao, report in an upcoming issue of *Applied Physics Letters (APL)* that they made a similar transistor from poly(hexylthiophene) but then crafted an organic LED alongside.

The Bell Labs LED shines brighter, because the team coaxes light from a highly luminescent small organic molecule known as ALQ, says Bao. The downside is that this material must be laid down in a vacuum, a somewhat cumbersome process. Although the Cambridge LED is not as bright, it is made with a polymer-based light emitter, which can be applied from a simple solution—a process that is easier to scale up to coat large areas. Sirringhaus notes as well that he and his colleagues should be able to improve the performance of their devices considerably, for they were able to get much better performance out of their transistor by finding ways to encourage the polymer to order.

Bao says that since she and her group submitted their *APL* paper, they too have made all-polymer integrated transistors and LEDs. The two groups say they are now pushing ahead with efforts to create full arrays of the devices by screen printing and inkjet printing. If they succeed, plastics will display a whole new image.

–Robert F. Service