

zero bias, which is proportional to the density of states available to electrons tunneling from the sample into the microscope's tip. In a conventional s-wave superconductor, there should be very few electronic states right at the Fermi surface: The differential conductance should be zero within a defined energy of the Fermi surface known as the superconducting energy gap. With the d-wave symmetry of high- T_c materials, that energy gap shrinks to zero at certain directions in momentum space—the nodal directions—but the density of states is still very small at the Fermi surface.

In the differential conductance image, most of the sample appeared black, corresponding to minimal conductance. But against this inky background shone a sprinkling of starlike spots. The high differential conductance at those stars indicated that the superconducting pairs had been broken and that a quasiparticle state had appeared in the center of the gap. The researchers were astounded at just how strong the differential conductance was: up to six times greater than the normal state conductance. All evidence suggested that the conductance peak could be ascribed to zinc atoms at the copper sites.

Seeing stars

The bright spots looked like many tiny crosses, all with the same orientation; a comparison of the spectroscopy with the topography confirmed that the arms of the crosses extended in the

directions of the a and b crystallographic axes of the copper oxide planes (see the bottom panel of the figure on page 17). These axes are also the directions of the nodes in the d-wave superconducting pair wavefunctions. A closer look revealed that each cross also featured a weaker cross pattern, superimposed on the first but rotated by 45° . Both crosses are evident in the false-color image in the middle panel of the figure; the logarithmic scale of intensity there somewhat exaggerates the secondary crosses. Clearly, the density of states in the energy gap does not fall off sharply with distance away from the central impurity site but rather undulates, with side peaks at the sites of surrounding copper atoms.

The appearance of the star-shaped intensity pattern bears out the predictions of a number of theorists.^{2,5,6} As one of those theorists, Alexander V. Balatsky (Los Alamos National Laboratory), explains it,⁷ the anisotropic state at the zinc site is like a full glass of water, with the surrounding energy gaps playing the role of retaining walls. But water can leak out at the nodes, so the impurity state has tails in that direction.

Other details of the observations, such as the weaker, rotated crosses lying along the directions of the lobes, remain unexplained. These details and others likely to be uncovered by STM studies will continue to challenge theorists.

The Berkeley-Tokyo researchers

are already studying the effects of a magnetic impurity—nickel—on the superconducting state; their results may have great relevance for theories that postulate a large role for antiferromagnetic correlations in the high- T_c pairing mechanism. The Berkeley group is also trying to build an STM that will operate at temperatures as low as 100 mK to enable measurements on strontium ruthenate, an unconventional superconductor (with T_c of only 1K) whose pairing state—strongly suspected to be p-wave—is still not convincingly established.

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Experiments Reveal How Heat Is Mixed into Cold Dense Water in the Abyssal Ocean

If the world's oceans relied only on molecular diffusion and smooth laminar flow to spread the Sun's heat, they'd consist of a thin Sun-warmed layer atop a mass of icy water. But other transport mechanisms are at work. In the North Atlantic, for instance, wind-driven currents push warm water from the Caribbean to the Arctic, where it cools, sinks, and flows back southward. And throughout its journey, the seawater is swirled and agitated by continent-sized gyres and centimeter-sized turbulent eddies.

Determining exactly how these mechanisms work is important for more than just solving ocean dynamics. The transport of heat in the oceans is one of the key ingredients and among the largest sources of uncertainty in the complex computer

By tracing the diffusion of a dye, researchers have found suggestive evidence that the moon promotes the flow of heat in the deep ocean.

programs (known as global circulation models) that are developed to investigate global warming. The better we understand ocean heat transport, the more confidently we can predict future climates.

For one heat transport mechanism—turbulent mixing in the deep ocean—the uncertainty has just been reduced. Reporting in a recent issue of *Nature*,¹ James Ledwell and his colleagues from Woods Hole Oceanographic Institution describe measurements of turbulent mixing at depths of 3500–5000 m off the east coast of Brazil. Their results can explain why

deep water leaving the Brazil basin northward is warmer and lighter than water entering the basin from the south.

To determine the degree of turbulent mixing, the Woods Hole team measured two related quantities: the turbulence-enhanced diffusion of a chemical tracer and what oceanographers call microstructure—centimeter-scale turbulent fluctuations.

The tracer release experiments began four years ago when the team set sail in the *RV Seward Johnson* from Rio de Janeiro to a point above the western flank of the Mid-Atlantic Ridge, the underwater mountain range that separates the South American and African continental plates. Once the team reached their destination, at 22° N, 18° W, they submerged a device to a depth of 4000 m and

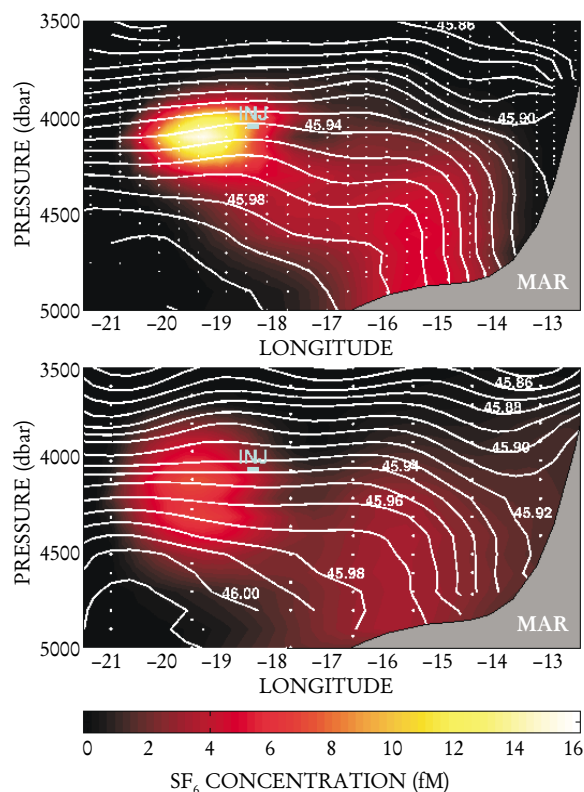
released its contents: 110 kg of sulfur hexafluoride, an easily detected compound that doesn't react with seawater.

Fourteen months after the release—and again, 12 months later—the team returned to the South Atlantic to measure how far the tracer had spread. On both cruises, they sampled the seawater at about 2000 locations in the ocean—each time measuring the concentration of SF_6 with their onboard gas chromatograph, which is sensitive to concentrations as low as 10^{-17} mol/l. The adjacent figure displays the team's results.

The microstructure measurements were made with a device called the High Resolution Profiler (HRP), which has the shape and size of a torpedo. Designed and built by Woods Hole researchers in the mid-1980s, the HRP is dropped untethered into the sea. As it descends (usually at a rate of 0.6 m/s), the array of transducers in its nose measures and records the centimeter-scale turbulent movement of the surrounding water. When its measurements are complete, it sheds its ballast and rises to the surface to await recovery and the extraction of its stored data.

The site of the experiments was picked for two reasons. First, Nelson Hogg (also at Woods Hole) and his colleagues had already measured the flow of bottom-hugging, dense, cold water into and out of the Brazil basin. Their finding, that water leaving the basin was warmer and lighter after its passage through the basin, implied that heat was somehow being mixed downward from warmer, shallower levels. The second reason for the locale was the likely influence of the Mid-Atlantic Ridge on turbulent mixing.

In oceanography, a key physical distinction is whether transport occurs along contours of constant density (isopycnals) or across neighboring contours of different density (diapycnal transport). Thanks to the dead hand of gravity, the oceans are largely stratified—in density, temperature, and salinity—and the ocean circulation takes place primarily along isopycnals and is isothermal. On the other hand, and working against gravity, diapycnal transport mixes heat and increases entropy. The questions addressed—and answered—by the Woods Hole group is where in the ocean, and under what certain cir-



TRACER CONCENTRATION 14 months (upper panel) and 26 months (lower panel) after release. "INJ" marks the initial release point of the tracer. "MAR" is the profile of the Mid-Atlantic Ridge. The contours indicate seawater density and are termed isopycnals. The figure clearly shows that the tracer spread not only along the isopycnals, but also across them. In the lower panel, 30% of the original dye has made its way to the ocean ridge, whose roughness enhanced the dye's spread. (Adapted from ref. 1.)

cumstances, diapycnal mixing can also be significant. As the figure shows, both sorts of mixing are clearly present: The dye spread across the isopycnals, as well as along them.

To translate the tracer concentrations into an estimate of the diapycnal diffusivity (defined as the flux of solute divided by its concentration gradient), Ledwell applied a simple one-dimensional model and found diffusivity values of $3 \text{ cm}^2/\text{s}$ at the release depth of 4000 m and $8 \text{ cm}^2/\text{s}$ at 4500 m. The diffusivity values derived from the microstructure measurements agree and also increase sharply with depth.

But the Brazil basin values are an order of magnitude higher than the values Ledwell, Andrew Watson, and Clifford Law found seven years ago² with tracer experiments in a quite different part of the Atlantic: 1200 km west of the Canary Islands at a depth of 310 m. Based on these earlier experiments, Ledwell had concluded that diapycnal mixing is negligible in the

shallow ocean. What, then, is different about the Brazil basin?

Stir it up

The answer does appear to be the disruptive effect of the Mid-Atlantic Ridge on transverse flows. But there's an extra, lunar twist. When plotted against time, the turbulent mixing (as indicated by HRP measurements of the depth-integrated rate of kinetic energy dissipation) and the estimated tidal speed (based on numerical models constrained by data from the Topex/Poseidon spacecraft) are remarkably similar. Not only does the dissipation rate have the same two-peaked profile as the tidal speed, but the peaks occur at the same two times a month—with a phase lag, as might be expected.

According to Kurt Polzin, one of Ledwell's Woods Hole coauthors, tidally driven mixing is sufficient to solve the mystery of how deep water is warmed as it passes through the basin. The key, Polzin believes, is the range of length scales at which tidal oscillations interact with topographic features. Flowing at speeds of 2–3 cm/s, tidally driven water in the Brazil basin makes an excursion of about 500 m before sloshing back when the tide turns. If those flows occurred over a flat surface, not much turbulent mixing would occur. In reality, the ocean floor at the Mid-Atlantic Ridge is both steep and rough. The steep slopes push the tidal flows upward, generating waves that radiate away from the bottom boundary, which in turn break as they propagate away. The spreading of the dye patch is a direct consequence of turbulence produced by these breaking waves.

One of the key features in describing the generation of the breaking waves is the character of the bottom roughness. As Polzin explains, geophysicists have measured the topography of the ridge and characterize it as fractal. That is, the topographic slope variance is unbounded as you go to smaller and smaller scales. "And that's crucial, because the smaller the scale of the roughness, the shorter the wavelength of the generated waves, and the more prone the waves are to breaking. A fractal surface provides lots of short waves."

Furthermore, because short waves attenuate more rapidly than long waves, the zone of turbulent mixing

does not extend far from its source. Indeed, HRP data reveal that 1000 m above the ocean floor the rate of turbulent energy dissipation drops by a factor of 100. Such a steep dependence on depth confines the effect of turbulence-driven mixing to the circulation of bottom and deep waters.

"It's exciting and wonderful

physics," says Christopher Garrett of the University of Victoria in British Columbia. Garrett, notes, however, that the tides, rather than being the prime mixing agent, could be a catalyst that interacts with other internal waves, such as those generated by storms on the surface. "But," he adds, "Kurt's model is a

bold and significant step forward."

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A Photon-Activated Switch Detects Single Far-Infrared Photons

The far-infrared (FIR) region of the electromagnetic spectrum, covering wavelengths between 10 μm and 1 mm, contains a wealth of information. In the laboratory, this range includes the vibrational and rotational spectra of molecules and the energy gaps of superconductors. And in astrophysics and cosmology, it is the realm of emissions from the earliest galaxies, which, due to their large redshifts, emit more than half of their energy in submillimeter radiation. Also in this spectral range is radiation from protostellar regions and planets, which are too cool to emit in the visible.

Detecting far-infrared radiation is difficult, however. The region falls between radio waves and visible light, and neither set of techniques developed for those regions can be extended readily into the gulf between them. Existing detectors in the far-infrared tend to be either bolometers, which measure the total absorbed power, or heterodyne detectors, which use reference frequencies to mix the absorbed radiation down to lower, more readily managed frequencies. Neither approach comes close to the single-photon sensitivity that is possible with photomultipliers in the visible and near-infrared.

In the first of what may be a new crop of more sensitive FIR detectors, Susumu Komiyama, Takeshi Kutsuwa, and Hiroshi Hirai from the University of Tokyo and Oleg Astafiev and Vladimir Antonov of the Japan Science and Technology Corporation (JST) have recently demonstrated FIR detection at the single-photon level using a novel detection mechanism in a quantum dot.¹ The device was developed as part of JST's Core Research for Evolutional Science and Technology program.

A sensitive electrometer

The device employed by the researchers, illustrated in the accompanying figure, is a semiconducting version of a three-terminal device

 The absorption of a single photon can turn the current through a quantum dot on or off.

called a single-electron transistor (SET). (See *PHYSICS TODAY*, January 1993, page 24.) At its heart is a quantum dot a few hundred nanometers wide, formed in a two-dimensional electron gas by applying negative voltages to electrodes patterned on top of stacked layers of GaAs and AlGaAs. The dot is weakly coupled to source and drain reservoirs through tunnel barriers and cooled in a dilution refrigerator to a temperature of about 50 mK. At this temperature, the behavior of the dot is dominated by the electrostatic energy of charging the dot's various capacitances, and the number of electrons on the dot is well-defined.

The quantum dot is placed in a strong magnetic field, which produces quantized energy levels—Landau levels—whose separation corresponds roughly to the electron cyclotron resonance frequency in the dot. For their detector, the experimenters used magnetic fields for which the lowest Landau level was filled and the second level had a small number of electrons occupying it. The lowest Landau level forms a ring close to the perimeter of the dot, while the second level forms an isolated core in the center. Conduction through the dot takes place through the lowest Landau level—but only when the electrochemical potential of the level lines up with that of the reservoirs.

An additional electrode near the dot functions as a control gate: The experimenters can shift the potential of the dot by changing the bias voltage applied to this electrode, thereby turning the conduction through the dot on and off. As the gate voltage is increased, it periodically pulls another electron onto the dot, producing a regular series of conductance peaks, as shown in the figure on the next page. The strong dependence of the

conduction on the gate voltage makes quantum dots, and SETs in general, ultrasensitive electrometers.

Flipping the switch

An incoming photon, if its energy is resonant with the Landau level spacing, can promote an electron from the lowest Landau level into the second level—that is, the isolated inner core of the dot. Once excited, the electron stays in the upper level for a long time—ranging from 1 ms to 1000 s or more, depending on the magnetic field—before dropping back down to the lower level. Due to the finite capacitance between the inner core and the outer ring of the dot, the extra charge on the inner core of the dot alters the potential of the lower level, which in turn shifts the values of the gate voltage at which the conductance peaks occur.

The gate voltage shift of the conductance peaks is larger than the widths of the conductance peaks. Thus a dot originally biased to be conducting, or "on," will become nonconducting with the absorption of a single resonant photon. The dot stays "off" until the excited electron drops back down into a vacancy in the lowest Landau level, at which time the dot is reset to its "on" position. A sequence of switching events is shown in the figure's bottom panel.

In traditional photon-assisted tunneling, an absorbed photon leads to the transport of only a few electrons. Here, in contrast, a million or more electrons can flow—or can stop flowing—in response to a single absorbed photon. The dot is sensitive to photons in the far-infrared, with wavelengths of about 200 μm and energies of about 6 meV. The absorption frequency of the detector can be tuned by tweaking the magnetic field, which changes the dot's level spacing.

Other approaches

Similar photon-activated switch behavior in a metallic single-electron transistor was reported in 1995 by