identification as a pentaquark is a conjecture that fixes the bottom of the multiplet's mass scale, all the other pentaquark states and their masses were predictions. What matters for the interpretation of the new NA49 results are the predicted six cascade baryons at the base of the triangle.

The Jaffe–Wilczek theory asserts that all six should have roughly the same mass. To distinguish the isospin-½ doublet belonging to the octet from the antidecuplet's isospin-3⁄2 quartet, they are labeled, respectively, $\Xi_{1/2}$ and $\Xi_{3/2}$. The observed $\Xi^{--}(1860)$ is unambiguously a $\Xi_{3/2}$, whereas the $Q = 0$ peak in the $\Xi^{-}(1320)\,\pi^{+}$ invariant-mass distribution could be indicating either a $\Xi_{1/2}$ or a $\Xi_{3/2}$, or both. But, if the evidence for reaction 1 survives, the observed $\Xi^{-}(1860)$ can only be a $\Xi_{1/2}$. That's because the group-theoretical rules for combining SU(3) multiplets forbid reaction 1 if the decaying $\Xi^{-}(1860)$ belongs to an antidecuplet.

So, the NA49 data would seem to require both antidecuplet and octet cascade states of mass around 1.86 GeV. Such a coincidence would be surprising in the skyrmion model, which also predicts an antidecuplet topped by the $\Theta^{+}(1540)$ but not an obligatory octet with degenerate cascade masses (see PHYSICS TODAY, September 2003, page 19). But precisely that mass degeneracy between antidecuplet and octet cascade states is a natural consequence of the correlated-quark model.

One might protest that, because flavor SU(3) is only an approximate symmetry, the observation of reaction 1 could simply be a symmetry-violating decay of the $\Xi^{-}_{3/2}$ (1860). If that's so, however, NA49 should probably also have seen the symmetry-violating decay of the $\Xi^{+}_{3/2}(1860)$ to $\Xi^{0}(1530) + \pi^{+}$ at a comparable rate. But the experiment, as yet, sees no hint of such a signal.

Pentaquark spectroscopy is off to a surprisingly vigorous start. Of course, the NA49 results have yet to be confirmed by other experiments. Theorists are especially eager to see data from detectors that can record neutral particles. "Whatever the final outcome, it's clear that a new spectroscopy has been born," says Jaffe. "For a particle physicist, it's a refreshing change to be working again with theories that make falsifiable predictions and experiments that make discoveries." CERN theorist John Ellis agrees: "Nowadays I check the preprint archive every morning for new experimental high-energy results," he says. "It's been a long time since I last did that."

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New Experiments Set the Scale for the Onset of Turbulence in Pipe Flow

Measurements of the stability of laminar flow bring us closer to answering one of the biggest outstanding questions in fluid mechanics.

In 1883, Osborne Reynolds published his landmark paper on the transition from smooth, laminar flow to turbulent flow in cylindrical pipes. Drawing water through a horizontal glass pipe, Reynolds injected a narrow stream of dye and looked for the onset of eddies as he varied the flow velocity and the water viscosity (dependent on water temperature). He found that the transition to turbulence was very sensitive to disturbances and typically occurred above a critical value of about 2000 for the ratio of UD/ν, where U is the average (or bulk) velocity, D is the pipe diameter, and ν is the kinematic viscosity.[1] This ratio, which parameterizes the relative strengths of inertial and viscous forces, is now known as the Reynolds number *Re*.

Understanding the nature of the transition to turbulence has been an ongoing quest ever since Reynolds's first experiments (and was the subject of Werner Heisenberg's PhD thesis in 1923). For pipe flow, the underlying Navier–Stokes equations, which describe the fluid dynamics of a system, have a laminar solution that's been found numerically to be stable for all Reynolds numbers. Indeed, in exquisitely controlled experiments, laminar flow at Reynolds numbers up to 100 000 has been observed.

And yet in practice, most pipe flows—at least for *Re* above about 2000, a typical value for a moderate flow of water from a faucet—are turbulent. Because laminar flow is linearly stable—that is, stable against infinitesimal perturbations—a finite-amplitude perturbation must be required to kick pipe flow out of that state and into a turbulent mode.

The nature of that transition is of more than academic interest. For a given pressure drop along a pipe, turbulent flow will result in a flow rate

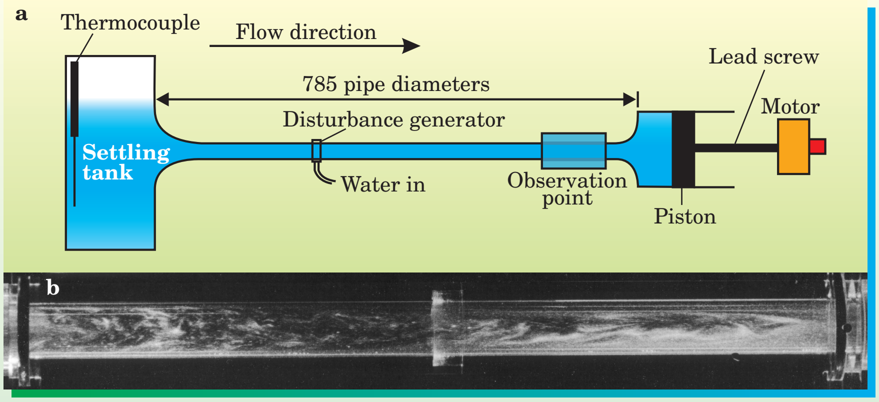

Figure 1. A long pipe for measuring the amplitude of perturbations needed to kick laminar flow into a turbulent state. **(a)** Like a long syringe, a motorized piston drew water from a settling tank along a 15.7-meter pipe. The effect on the flow from an additional pulse of water injected along the pipe was monitored by observing the reflection of light off platelets in the water. (Adapted from ref. 2.) **(b)** Turbulent flow seen for a Reynolds number of 2200 in two of the 105 sections of acrylic that make up the pipe. (Courtesy of B. Hof, P. Treacher, and T. Mullin.)

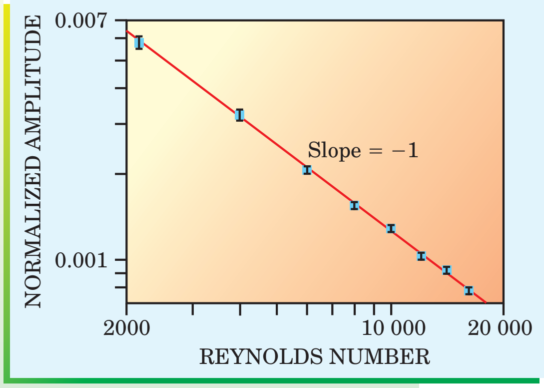

Figure 2. Turbulence threshold scaling. The amplitude of the perturbation required to establish turbulence scales inversely with the Reynolds number of the flow when the injected flux is normalized by the flux flowing through the pipe. (Adapted from ref. 2.)

an order of magnitude smaller than laminar flow. To avoid large pressure and flow fluctuations associated with the turbulence transition, oil and gas pipelines are usually operated in the less-efficient turbulent regime. The ability to predict—and perhaps eventually control—the transition to turbulence could be a real boon.

In recent experiments,[2] Björn Hof, Anne Juel, and Tom Mullin of the University of Manchester have measured how the threshold amplitude of turbulence-producing perturbations in pipe flow scales with *Re*. "They have unambiguously determined the thresholds in controlled experiments for the first time," comments Dan Henningson, a fluid dynamicist at Sweden's Royal Institute of Technology (KTH).

Of pipes and planes

Pipe flow is just one case of important flow scenarios in fluid dynamics. The other two canonical shear flows are plane Couette flow and plane Poiseuille flow. In plane Couette flow, the fluid channel is defined by parallel walls that are moving relative to each other; fluid adjacent to each wall has the same velocity as the wall, and in laminar flow there is a linear velocity profile from one wall to the other. (In a variant geometry, Taylor–Couette flow, the fluid is confined between differentially rotating coaxial cylinders.)

Plane Poiseuille flow is confined by stationary parallel walls and is typically driven by a pressure gradient along the channel. Fluid next to the walls is stationary, which leads to a laminar parabolic velocity distribution across the channel. Pipe flow, also called Hagen–Poiseuille flow, is similar to plane Poiseuille flow in that the walls are stationary and the flow is again typically driven by a pressure gradient. As a consequence of the three-dimensional cylindrical geometry, theoretical treatments of pipe flow tend to be more difficult than that of its planar cousins.

Like pipe flow, Couette flow is linearly stable at all Reynolds numbers; plane Poiseuille flow, in contrast, develops an instability at a finite *Re*. Bringing modern mathematical ideas to bear on the turbulence transition in all these flows has become prevalent over the past 10 years.[3] A key question that's been looked at is how the threshold perturbation amplitude ε scales with *Re*: If $\varepsilon \sim Re^{\gamma}$, as is generally assumed, what is the value of γ? Earlier studies placed γ between -1 and $-7/4$. Looking at the asymptotic behavior of the Navier–Stokes equation, for example, Jon Chapman of the University of Oxford has predicted that γ is -1 for Couette flow and $-3/2$ for plane Poiseuille flow below its instability.[4]

A big syringe

To set about looking experimentally for the threshold scaling in pipe flow, Mullin and colleagues built a special pipe, illustrated in figure 1a, that is 15.7 meters long, 785 times its 20-mm diameter. One cannot buy such a long straight pipe, so the Manchester group fabricated theirs out of 105 machined sections of acrylic, each 150 mm long. Having a long pipe is important because it takes time to develop a steady flow, particularly at larger *Re* (corresponding to faster flow rates). After aligning the sections with a laser, the team succeeded in generating laminar flow through their pipe at a very high *Re*, 24 000 (corresponding to a flow rate of 3 m/s). Such rapid laminar flow was a testament to the quality of the assembled pipe, which took four years to create, align, test, and calibrate.

Most experiments studying pipe flow have driven the flow by applying a pressure gradient along the length of the pipe, with either an elevated source of fluid or, as Reynolds originally used, a lowered drain at the end of the pipe. Mullin and coworkers took a different tack: Like a big syringe, a computer-controlled piston pulled water through the pipe at a specified rate from a large settling tank. That approach has the advantage of allowing direct control of the mean fluid velocity and hence *Re*. In contrast, for flows driven by pressure gradients, the velocity—and *Re*—will vary during the transition to turbulence. For looking at how the threshold depends on *Re*, the ability to fix *Re* is important.

The perturbations to the flow were generated using an automobile fuel injector connected to a fast-switching pump. That configuration allowed the experimenters to inject tangentially a controlled flux of water for a controlled duration through six holes evenly spaced around the pipe. The injected flux was the experimental knob corresponding to the perturbation amplitude; typical values were a few tenths of milliliters per second, two to three orders of magnitude smaller than the total flux through the pipe.

The threshold-measuring experiments were very time consuming. The researchers took 40 measurements to determine each threshold for a given *Re* and injection duration. To ensure that the observed flow characteristics were due solely to the controlled perturbation and not to any spurious background influences such as temperature gradients in the water tank,

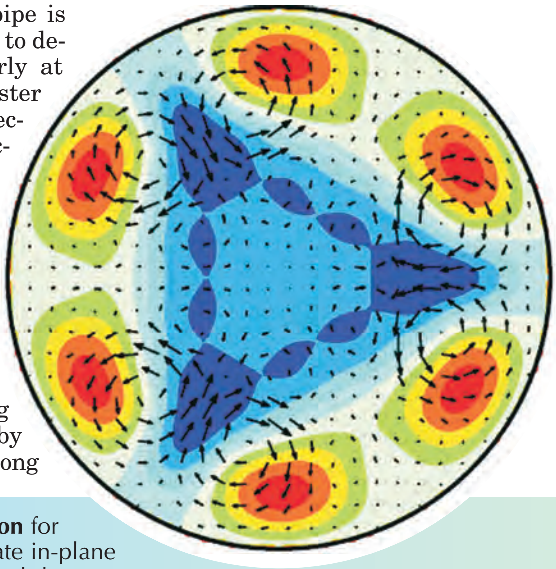

Figure 3. A traveling-wave solution for flow in a pipe. The vectors indicate in-plane motion. The colors denote the local downstream flow velocity: blue is slow and red, fast. The downstream motion has been averaged over a wavelength. Such states may play a role in the transition from laminar flow to turbulence. (From ref. 6.)

they waited for an hour before each run to give the system time to settle. The flow was imaged by monitoring the reflection off anisotropic platelets that had been dispersed in the water (see figure 1b).

Water injected into the pipe gets pulled along by the flow; how far an injected pulse got carried along the length of the pipe turned out to be a key parameter affecting the system's response. When the Manchester group plotted their threshold data against the spatial length of the perturbation, the results for different *Re* collapsed onto a single curve. The threshold depended sharply on that length for short pulses, for which larger amplitudes were needed; otherwise the disturbances decayed as the injected pulse traveled down the pipe. The threshold amplitude for perturbation lengths longer than about six pipe diameters became independent of length.

For comparison to theory, the natural means of describing the threshold amplitude is the volume flux of the perturbation normalized by the flux in the pipe. When plotted this way, the threshold amplitudes showed an inversely proportional dependence on *Re*—that is, a scaling exponent γ of –1, as seen in figure 2. That scaling relationship extends over an order of magnitude in *Re*, from 2000 to nearly 20 000. "What's interesting is that the scaling looks so clean at relatively low Reynolds number," comments Rich Kerswell of the University of Bristol. The scaling exponent of –1 agrees with calculations by Chapman, based on the growth of transient fluctuations, but it's not yet clear whether that mechanism is what's at work in the Manchester experiments.

The nature of the transition

Of course, determining the size of the kick needed to drive a flow turbulent is only one part of understanding the turbulence transition. The mechanism by which the turbulent state develops is also vital to a full understanding.

The laminar flow state can be viewed as an island (or, technically, a basin) of stability in the sea of phase space. The Manchester work has measured how the island size decreases as *Re* increases. But what happens when a sufficiently strong perturbation knocks the system off the island?

A mathematical solution to that question may be emerging. Fabian Waleffe of the University of Wisconsin-Madison has formulated a so-called self-sustaining process that leads to nonlinear, three-dimensional traveling-wave solutions of the Navier–Stokes equations for plane Couette and plane Poiseuille flow.[5] Holger Faisst and Bruno Eckhardt of the University of Marburg[6] and Hakan Wedin and Kerswell at Bristol[7] have recently reported a class of similar traveling-wave solutions in pipe flow.

Those solutions, one of which is shown in figure 3, have a discrete number of faster-moving streaks of fluid near the wall and slower streaks near the center, and vortices around which the fluid spirals as it travels down the pipe. Hof, now with Frans Nieuwstadt at the Delft University of Technology, has found some evidence for such states in pipe flow. Although the traveling-wave flow states are unstable, they may represent the first indications of increasing complexity in phase space, which ultimately harbors a turbulent attractor as *Re* increases.

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Sea-Level Rise Exacerbates Coastal Erosion

A recent analysis of more than a century's worth of data forebodes severe losses of coastal land.

On 7 March 1962, what became known as the Ash Wednesday Storm struck the mid-Atlantic coast of the US. Boosted by a high spring tide, the storm's waves grabbed sand normally out of reach and dumped it in offshore shoals. In Delaware, the storm pushed the shoreline back 80 meters.

Today, Delaware's beaches have largely recovered, thanks to the steady action of long-wavelength waves that move sand from shoals to beaches. This take-and-give plays out on beaches all over the world. It's responsible for the remarkable longevity of barrier islands and, indeed, for the formation of beaches in the first place.

Short-term local recoveries, however, belie a protracted global trend. At least 70% of the world's beaches are in what seems like permanent retreat. An increase in storminess or a decrease in replenishment could be responsible for the long-term loss, but meteorological records of the past century evince no such changes.

Instead, as Keqi Zhang, Bruce Douglas, and Stephen Leatherman of Florida International University demonstrate in a forthcoming paper, the culprit appears to be sea-level rise.[1] As Earth's climate warms, seawater expands and long-frozen glaciers and ice caps shed meltwater into the ocean. The most recent estimates put the mean global increase in sea level at 1.5–2.0 millimeters per year.[2] Sea-level rise doesn't by itself erode beaches. Rather, it acts like a gradual, relentlessly swelling tide that extends the destructive power of storms.

That finding might not seem surprising. However, the FIU researchers have also vindicated a 42-year-old model that quantifies the relationship between sea-level rise and erosion. Formulated by pioneering coastal engineer Per Bruun, the model makes a grim prediction for the sandy beaches of the US East Coast and elsewhere: Without expensive remedial action, each centimeter of sea-level rise will be accompanied by a loss of about a meter of beach. Within a century, oceanfront properties, like those in figure 1, could end up literally at the front of the ocean.

Shifting sands

Quantifying the relationship between sea-level rise and erosion isn't easy. The short-term movement of sand perpendicular to the shoreline (cross-shore) is much stronger than any change associated with sea-level rise. And at many beaches, the movement of sand parallel to the shore (longshore) is much stronger than in the cross-shore direction.

Like the physicist's spherical cow, Bruun's 1962 model sweeps those difficulties under a rug of simplification.[3] His starting point is an ideal beach that has no longshore transport. He defined a closure depth D_C below which waves lack the energy to shape