

PHYSICS

Tipping the Scales—Just Barely

Researchers are making big strides in a race to build nano-sized devices capable of weighing a single proton

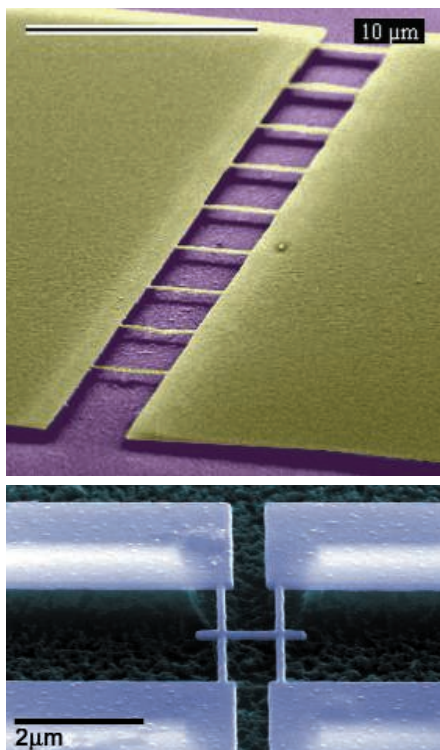
Next to Kate Moss, Michael Roukes may be the most obsessive weight watcher on Earth. Roukes, a physicist at the California Institute of Technology (Caltech) in Pasadena, isn't particularly worried about putting on or shedding a kilogram. He's thinking much lighter than that. In the 4 April issue of *Nano Letters*, Roukes and colleagues report making the most sensitive mechanical scale ever, capable of registering 0.00000000000000000007 grams, or 7 zeptograms.

Even that achievement—weighing the equivalent of 30 xenon atoms—isn't enough to satisfy him, however. Within 2 years, Roukes and colleagues hope to register the weight of individual hydrogen atoms, a mere 1.66 yoctograms ($1.66 \cdot 10^{-24}$ grams). For perspective, a yoctogram is to a gram as a gram is to the mass of the continental crust under Europe. Top that, Kate.

Roukes's team isn't alone in its effort. Numerous groups around the globe are pushing the boundaries of ultrasensitive mechanical mass detectors. Most researchers, including Roukes, are seeking practical applications such as nanoscale versions of mass spectrometers, large and ubiquitous machines used for weighing molecules. A few, such as the Caltech group, are also hoping that their scales are sensitive enough to pick up individual protons. "It's within reach," says Rashid Bashir, a ultrasensitive mass detection expert at Purdue University in West Lafayette, Indiana. "But it won't be easy."

The race to zeptogram sensitivity began heating up in 2003, when a pair of researchers at Oak Ridge National Laboratory in Tennessee reported that they had created nanoscale devices capable of registering organic compounds with a mass of 5.5 femtograms (10^{-15} grams). Harold Craighead and colleagues at Cornell University leaped past that figure in April 2004 with a report that they could detect mass changes down to the attogram level (10^{-18}). Kamil Ekinici, a former postdoc of Roukes who now runs his own lab at Boston University, patented an attogram detector with his mentor back in 2001, although their results didn't hit the scientific literature until May 2004. Now, with their *Nano Letters* paper, Roukes and Ekinici have taken the sensitivity to nearly the single-zeptogram scale.

There are many ways to measure mass. Most mechanical scales are made from tiny wires of silicon or other sturdy materials suspended over a surface. The scales are anchored either on one end, like a diving board, or at both ends, like a bridge. Researchers trigger oscilla-



Lightweights. Nanoscale sensors made by teams at Caltech (*above*) and Boston University (*top*) register tiny weights by creating oscillations in wirelike slivers of material and then gauging how those oscillations change when a tiny collection of atoms or molecules is sprayed on top.

tions in the wires and track how the frequency of those oscillations changes when a tiny speck of mass is added.

In their paper, Roukes, Ekinici, and Caltech colleagues describe how they constructed tiny bridges from silicon carbide and connected a wire to each end of the bridge. They then placed their device in a vacuum chamber and within a large magnetic field, passing a current through the silicon carbide bridge from one wire to the other. The motion of the electrical charges in the magnetic field exerted a sideways force on the bridge, essentially plucking it like a guitar string and causing it to oscillate up and down.

The team then used a specially designed electrical feedback loop to make it vibrate at a steady frequency of either 133 or 190 megahertz. This motion created a steady pattern of voltage changes between the wires at either end of the bridge. The researchers then sprayed xenon atoms or nitrogen molecules through a specially designed shutter in the vacuum chamber. When the extra atoms landed on the bridge, the added

mass slowed the bridge's vibrations, causing a change in the pattern of voltage readouts.

Ekinici says that since 2002 the team has improved the sensitivity of its apparatus 1000-fold. But he says it will take another such jump to detect individual hydrogen atoms. "This approach has very good potential to go to higher sensitivity," Ekinici says. To succeed, however, Ekinici and Roukes will need to make slightly smaller, more responsive bridges, get them to oscillate at a slightly higher frequency, and tweak the feedback circuitry to improve detection. Each advance has already been demonstrated independently; now Roukes's current team is working on putting them all together.

Other groups are also hard at work. One, led by Andrew Cleland at the University of California, Santa Barbara, for example, is using thermal energy to push an oscillating beam right up to a critical point, at which a tiny amount of added mass will push it over the threshold and cause the beam to oscillate at a markedly different frequency. But Cleland concedes that Roukes's team is the current leader.

The ability to weigh individual hydrogen atoms is expected to stimulate interest in nanomechanical mass sensors. Much of the payoff will likely come in differentiating the weights of different biomolecules, such as proteins. Such an advance could lead to nanoscale mass spectrometers capable of weighing individual molecules.

Current mass spectrometers, by contrast, start with millions of molecules and compute their average weight. By looking at single molecules, researchers could detect minute changes, such as proteins with a very slight sequence change or ones labeled with different isotopes. They could also track the weights of neutrally charged molecules, a feat mass spectrometers cannot perform because they use the charge of different molecules to propel them through the mass detector. By using the lithographic tools of the electronics industry, researchers also could make huge arrays of nanoscale mass spectrometers that look at vast numbers of biomolecules simultaneously.

Efforts to use nanomechanical sensors to weigh biomolecules are well under way. Craighead's group at Cornell, for example, reported in 2001 that it was able to detect single cells with attogram-scale masses. More recently, researchers have tracked individual viruses and DNA molecules. "But it will take a bit more time" to make practical devices, Ekinici says.

One challenge is that biomolecules exist in watery environments rather than in vacuums. But operating nanoelectromechanical systems devices in water causes the molecules to stick to their cantilevers and change their motion. Numerous teams are working on specialized coatings to fend off nontarget molecules or latch onto targeted ones. Their success promises to open new windows into the biochemistry of individual cells.

—ROBERT F. SERVICE