O atom on the tip approaches a surface-bound H atom, the two experience an attractive force, represented by the dotted line in the figure. The attraction sets up a tug-of-war for the H atom between the tip and the surface.

The tip always loses the battle: The terminal O atom already has one H atom bound to it, so the attraction it feels to a second H is weaker than the chemical bond holding the H to the surface. In fact, the more strongly the H clings to the surface O atom, the more weakly it's attracted to the tip.

To relate the AFM force measurements to conventional notions of acidity, Meyer had the idea to calculate the force between the model tip and the H atoms of a suite of small molecules whose acidities are known. From those calculations, he derived a linear calibration, shown in figure 2, that relates the AFM force to proton affinity—how strongly each molecule holds on to its H atom rather than releasing it as an H^+ ion into the surrounding solution. A more attractive (that is, more negative) force to the AFM tip corresponds to a lower proton affinity and thus a higher acidity: All the molecules with "acid" in their names are clustered in the lower left corner of the figure.

The calibration line makes it possible to convert the measured AFM forces on a surface to proton affinities for each surface site. The water OH site, as plotted in black, is the least acidic site on the In_2O_3 surface; the γ site, as plotted in blue, is the most. Using the same In_2O_3 AFM tips, the researchers have begun extending their measurements to other surfaces, including titanium dioxide (brown) and zirconium oxide (purple).

So far they've studied only regular surfaces with just one or a few types of surface O sites. Eventually, though, they want to look at surfaces with steps, defects, and impurities to see how those features affect surface chemistry. "The next big open challenge," says Diebold, "is to do all the same measurements in liquid water."

Johanna Miller

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Macroscopic systems can be controllably entangled and limitlessly measured

Two oscillating membranes demonstrate correlations forbidden by classical physics.

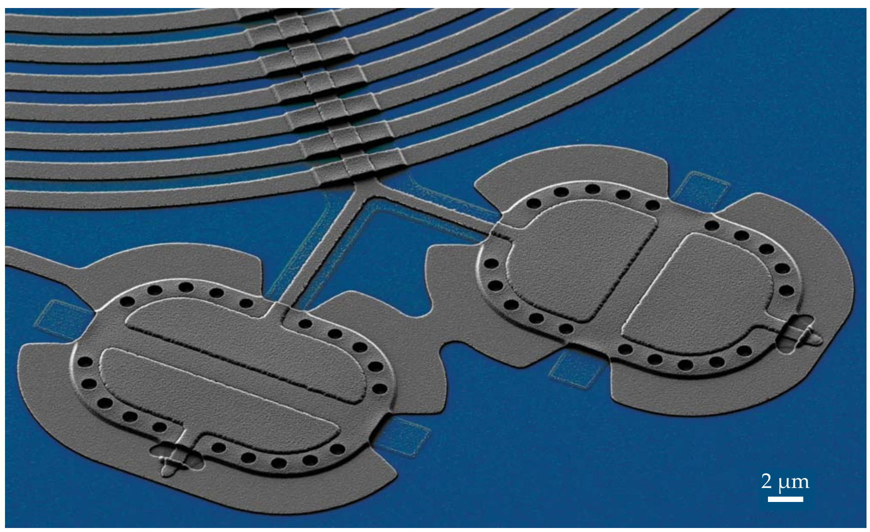

FIGURE 1. ALUMINUM DRUM membranes suspended above a sapphire substrate vibrate in a direction perpendicular to it. Each membrane forms the top plate of a capacitor, while the bottom plate is fixed to the substrate. A spiral inductor links the capacitors to form a microwave cavity. Radiation pressure from microwave pulses that impinge on the cavity drives the two membranes' oscillations to an entangled state. (Image courtesy of Florent Lecocq and Shlomi Kotler/NIST.)

What Albert Einstein skeptically referred to as "spooky action at a distance" has turned out to be one of the most important drivers of quantum technology. That spooky action, or entanglement, describes a phenomenon in which measuring the state of one particle instantaneously generates effects on another particle. The entangled particles' measurable properties are so strongly correlated that the relationship can't, statistically, have happened by chance or be explained by classical physics.

Although quantum effects are most easily observed in tiny objects, quantum mechanics is not limited to the atomic scale. In principle, objects of all sizes should behave according to quantum mechanics. But at the macroscale, quantum effects are all but impossible to detect because of limits of modern measurement tools and the tendency of larger objects to interact with noisy environments.

To bridge the gap between our daily classical experience and our expectation that quantum mechanics is universally valid, experimentalists seek quantum phenomena on larger systems. Pushing the envelope on systems in which quantum effects are observable could eventually reveal whether quantum theory does have a physical boundary.

Two research groups now report direct verification of macroscopic quantum effects that cannot be described by classical physics. In one paper, Shlomi Kotler, now at the Hebrew University of Jerusalem, and his colleagues at NIST in Boulder, Colorado, deterministically generated and directly measured the correlations needed to verify entanglement between separate macroscale mechanical objects.[1] In the other, Laure Mercier de Lépinay and her colleagues at Aalto University in Finland developed a similar system in which they could make quantum measurements that appeared to be at odds with fundamental limits associated with the Heisenberg uncertainty principle.[2]

Both sets of experiments involved pairs of micrometer-scale drumhead membranes that oscillate together in near-perfect synchronization. That scale is large compared with the atomic-scale systems in which quantum effects are usually observed. Besides enlarging quantum theory's observed realm, those effects—and the ability to manipulate and detect them—could also lead to new designs for logic gates and enhanced measurement techniques.

Mechanical revolution

Quantum effects are most readily observable in atoms and subatomic particles. For example, excited atoms can decay by emitting two photons within nanoseconds of each other. When those photons are emitted in opposite directions, conservation of angular momentum requires that their polarizations be correlated. Knowing one's polarization provides irrefutable information about the other's: the two photons are entangled.

Other strategies can be used to entangle physically distant atomic particles. Holding pairs of ions in traps and exciting them to a state from which they emit oppositely polarized photons causes the ions to end up in two different states. If the two photons are detected simultaneously, measuring the emitted light reveals one ion's resulting energy state, which must be opposite to that of the other ion. (See PHYSICS TODAY, November 2007, page 16.)

Entanglement has also been demonstrated in systems with mechanical degrees of freedom. In 2009 NIST researchers demonstrated entanglement in a pair of atomic-scale mechanical oscillators.[3] Pairs of vibrating ions, kicked into motion by a laser beam, behaved like two balls connected by a spring. The pairs vibrated in perfect unison, even when separated in space. That entangled behavior resulted from utilizing the ions' internal spin states.

But what about a much bigger mechanical oscillator, one with trillions of atoms? Experiments that use vibrating micron-scale membranes, fabricated as part of separate cavities and set into motion by microwave- and optical-frequency radiation, have already shown evidence of entanglement.[4,5] Photons scattered off the resonators and captured by detectors or made to interfere with each other match what would be expected if the vibrations were perfectly correlated. But unlike the new work, those experiments were either nondeterministic or they relied on complicated inferences and ad hoc subtraction of noise from amplifiers used as part of the readout.

Different drum

Deterministically producing and directly verifying entanglement in a system that's much larger than atom-scale, without relying on complicated inferences, is a different ballgame. Kotler, working with John Teufel and other colleagues at NIST, fabricated two oblong 10-μm-long aluminum drumhead membranes that were connected via a resonant cavity, as shown in figure 1. Each membrane was effectively a plate in a vibrating capacitor, coupled to a microwave-frequency AC circuit.

Two incident microwave pulses cooled the devices and steered them into synchronized oscillations. The pulses were generated at two different frequencies that inextricably linked the membranes. Had the membranes responded independently to the pulses, one would have heated up and the other would have Doppler cooled. Instead, one membrane's interaction with photons generated by the other's oscillation created entangled motion.

The motion mimicked that of two pendulums swinging with equal amplitude and opposite velocity, depicted in figure 2a. "They're tiny trampolines. Each one can go up and down. The name of the game is to synchronize their motions perfectly," says Kotler. (See the article by Keith Schwab and Michael Roukes, PHYSICS TODAY, July 2005, page 36.)

When another microwave pulse was incident on the oscillating membranes, the reflected light was Doppler shifted in a way that carried information about each membrane's position and momentum. By amplifying the readout signal immediately on its exit from the device, Kotler and his colleagues ensured that the measured signal could be clearly distinguished from noise.

Unsurprisingly, a single measurement of a pulse-driven oscillation did not show any clear connection between the two membranes. But by repeating the experiment 10 000 times and charting the evolution of the membranes' movements, the researchers found that the instantaneous positions tracked one another with precision beyond the threshold permitted by classical physics. That perfect correlation, plotted in figure 2b, is a hallmark of quantum entanglement. "This shows both that these kinds of large mechanical systems can be controllably entangled and measured with high enough precision to directly see the entanglement," says Aashish Clerk of the University of Chicago.

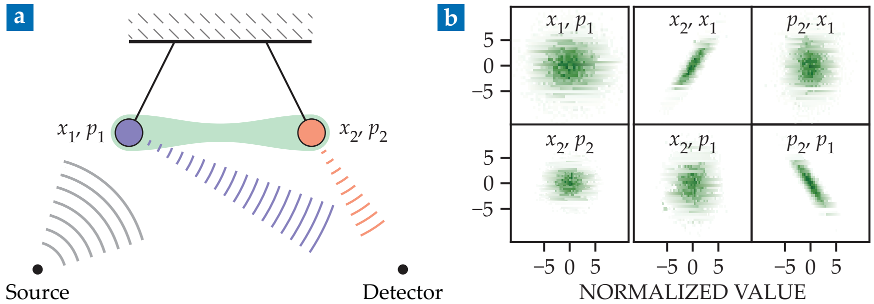

FIGURE 2. MECHANICAL OSCILLATORS in an entangled state, like the ones shown in figure 1, mimic the motion of two pendulums. **(a)** Microwave radiation, Doppler-shifted as it reflects off the pendulums, carries information about each oscillator's position (x_1 and x_2) and momentum (p_1 and p_2) and verifies the entangled state (green shaded region). **(b)** Full tomography directly shows the entangled state of macroscopic mechanical objects. A 10 000-repetition experiment that sets the membranes into entangled motion reveals the membranes' strongly correlated positions (x_1, x_2) and anticorrelated momenta (p_1, p_2). Each membrane's individual state (x, p) is consistent with a Gaussian distribution having large variance, which indicates that energy has been added to the system. Variables are normalized so that the ground state of each membrane has variance ½. (Adapted from ref. 1.)

Virtual measurements

Simultaneously measuring the position and momentum of an object should be impossible. According to Heisenberg's uncertainty principle, precisely observing an object's position has a perturbing effect on the object's momentum. That perturbation, called quantum back action, places a limit on how precisely position may continuously be measured. Might that quantum limit be evaded in a mechanical system?

To find out, Mercier de Lépinay and her colleagues also created entangled aluminum membranes. Their approach was to create a single virtual oscillator from two vibrating membranes, housed in separate microwave cavities. The membranes' stable entangled motion was driven collectively by microwave beams. Microwave beams of slightly different frequencies ensured that the oscillating membranes in each cavity moved in a coordinated but not identical way, vibrating in opposite phase to each other.

The motion of the membranes mimicked that of two objects, one with an effective negative mass, each attached to a coiled spring and coupled to a cavity. The coupling between the entangled membranes caused their momenta to change by the same magnitude when the same force was applied to both. However, because of its negative mass, one of the oscillators was displaced in the opposite direction. The result was an effective single harmonic oscillator that was delocalized from the component oscillators and whose position and momentum commuted with one another.[6]

By treating the membranes as a single virtual entity, the researchers could make direct observations of the entangled system without destroying its state. The uncertainty associated with each membrane canceled out, or was hidden in the part of the system that wasn't directly observed—the momenta of the individual membranes. "The uncertainty principle holds for one degree of freedom, and it is a law of nature. We can bypass it in a multimode system," says Mika Sillanpää, also of Aalto University.

Observing the single virtual oscillator allowed for complete measurement of its position while ensuring that quantum back action did not disturb the system's overall state or destroy its entanglement. "This is the first experiment to realize this kind of physics using only mechanical degrees of freedom," says Clerk.

Future tech

The Aalto team's virtual system is what's known as a quantum mechanics–free subsystem. It provides a possible path toward measuring extremely weak classical forces that act on the system, while circumventing the measurement limits imposed by quantum mechanics. The measurement technique could be applied to develop sensors that exceed the abilities of their classical counterparts.

The NIST team's pulse-driven entangled system could be further developed into an information-processing system, with each membrane pair serving as a qubit. Doing so would require ensuring that a measurement clearly stands out above the noise. For two membrane pairs, applying a multistep logic protocol in which one step depends on the outcome of the previous step would demonstrate that each logic gate measures above the system's noise and advances to the next step in a useful manner, according to Kotler. Eventually, combining multiple membrane pairs linked by wires could lead to a quantum processor based on entanglement.

Compared with atomic devices, the vibrating membrane platform can be easily manufactured and manipulated. It provides a tool for exploring the limits of quantum phenomena and creating useful devices at the macroscale.

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