PHYSICS

Quantum Squeeze Wrings Uncertainty From Atom Waves

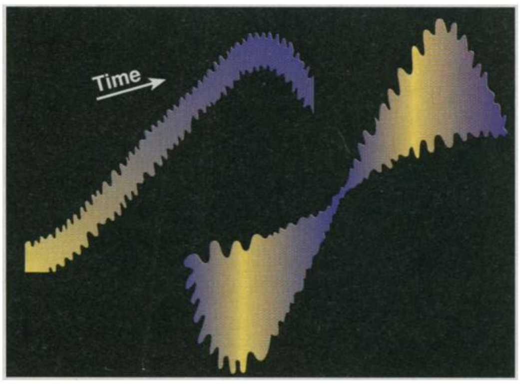
Researchers trying to make ultraprecise measurements of any physical quantity, such as a particle's location or a wave's frequency, soon run into difficulties posed by the oddities of quantum mechanics. The electromagnetic field that propagates light, for example, is suffused with random fluctuation—a seemingly inescapable quantum "noise" present even in complete darkness. Until the mid-1980s, physicists thought they would never be able to obtain a perfectly clean light wave to carry out ultraprecise measurements. Then, they found a way to "squeeze" the quantum fluctuation in part of a light wave to levels below that found in complete darkness, known as the vacuum level—at the cost of making another part of the light wave noisier. Now, a group at the University of Michigan has made that same quantum trade-off in another realm: phonons, wavelike vibrations of atoms in solids.

Like light waves, phonons suffer from "noise"—fluctuations at the vacuum level that prevent a solid's atoms from ever becoming completely still, no matter how low the temperature. As Michigan's Roberto Merlin puts it, the position of every atom resides inside a small bubble of quantum uncertainty. Now, as Merlin and his team report on page 1638, they have delivered ultrafast pulses of light to a sample of potassium tantalate, thus squeezing some noise out of the phonons at certain times while making them noisier at others, rhythmically expanding and contracting the bubbles of uncertainty. "In a sense, it's like momentarily cooling a solid" to previously unattainable low temperatures, says Merlin.

"It's the first time that this quantum phenomenon has been observed in material waves," says Joseph Birman of the City College of New York. "Achieving this is marvelous." As Bell Labs physicist Richart Slusher, one of the pioneers of squeezed light, explains, physicists get a thrill from eluding—if only briefly—the limits set by quantum mechanics: "It's very nice to be able to manipulate any field at the quantum level." Still, everyone agrees that applications lie a long way off; even squeezed light has yet to be put to work for high-precision measurements, although "we will get there," Slusher says.

Merlin's group has spent the past several years refining the art of using ultrafast laser pulses to trigger vibrations in solids. To produce the squeezed phonons, the team fired a pulsed laser beam, with a repetition rate of 85,000 times per second and pulses just 70 femtoseconds long, at a piece of potassium tantalate 0.5 millimeter thick, cooled to just 10 kelvins. Because potassium tantalate is transparent, the laser pulses penetrated into the material. There a process called second-order Raman scattering captured energy from light, turning it into pairs of phonons spreading in opposite directions like waves on an atom sea.

Phonons normally travel with frequencies characteristic of the material they are passing through, but the kick delivered by the laser pulses generates phonons that are slightly out of step with their normal frequencies. The effect of this mismatch is to play tricks on the random fluctuations of the atoms, explains Merlin.



In a bind. A normal phonon *(left)* has a constant uncertainty, shown here as thickness. In a squeezed phonon, the uncertainty gets pinched.

Imagine all the atoms of the solid as swinging pendulums. All the pendulums are at different stages of a swing: Some have swung up to their maximum height, some are at their lowest point, and some are in between—their fluctuations are entirely random. The effect of the laser pulse is that of delivering a vertical hammer blow to all of the pendulums. Those pendulums at the bottom of their swing will not be affected, those at the top will receive a strong impulse downward, and those partway up or down, a weaker push down.

The overall effect is to push the randomness of the pendulums into an oscillation. They first shift toward swinging in concert—a less random state that wrings the noise out of the phonon—then drift back toward a state more random than they were originally, and finally return to synchrony again. Thus, the atoms pulsate in and out of their squeezed state over time: Their bubbles of uncertainty expand and contract periodically, Merlin says. Because squeezing the uncertainty in the atoms' positions risks violating the Heisenberg uncertainty principle—a cardinal law of quantum mechanics that says you can never know with complete certainty both of a pair of linked variables, such as position and momentum—the uncertainty in the atoms' momenta increases when the position uncertainty is squeezed.

Each phonon is mathematically described by an equation called a wave function, whose "thickness" represents the quantum uncertainty in the positions of the atoms propagating the phonon. Normally, this thickness would be relatively constant, but the squeezing periodically pinches the thickness of the function. At these pinches, "the width of the wave [function] becomes smaller than the vacuum [fluctuations]," says Philippe Grangier of the Institute of Theoretical and Applied Optics in Paris. And because of the properties of potassium tantalate, the researchers were able to detect this pinching with a second "probe" beam.

In many materials, phonons can come in a variety of frequencies, so the periodic squeezing associated with the phonons would come at many different intervals, making it impossible to see a squeezed state through this tangle of signals. But in potassium tantalate, many of the phonons cluster around a specific frequency. All these phonons beat together, so that their squeezed states create a clear signal—a regular change in the material's refractive index—for the probe beam to pick up. Although the signal is clear, the squeezing was not huge: Merlin says the team managed to reduce the uncertainty in the bubbles' diameters by one part in 1 million. Since the original experiments, the Michigan team's laser setup has been out of action. Merlin says now that it is working again, he is confident of squeezing the uncertainty bubbles by one part in 10,000.

The Michigan team is now working to extend the technique to squeezing magnetic fluctuations in solids. "We know how to do it," says Merlin. Although they do not yet foresee practical applications for their squeezing technique, they do expect some interesting basic physics. Phonons are thought to have a role in high-temperature superconductivity, for example, and potassium tantalate has a crystal structure similar to that of the new superconductors. As a result, phonon squeezing might yield insights into the still-mysterious mechanism of high-temperature superconductivity. Slusher agrees: "Phonons are responsible for lots of phenomena in solids, so squeezed states must be of interest."

–Daniel Clery