QUICK STUDY

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Squeezing quantum noise

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You can't beat the Heisenberg uncertainty principle, but you can engineer systems so that most of the uncertainty is in the variable of your choice. Doing so can improve the precision of delicate measurements.

Most of the time, an imperfect measurement technique can be blamed for any deviation from the actual value of the variable you are trying to observe. However, in the probabilistic world of quantum mechanics, the observable properties of a physical system are truly uncertain; identical measurements on the same particle will result in different values even if each individual measurement is perfect. The Heisenberg uncertainty principle states that fundamental physics will limit how small the uncertainty in given pairs of observables can be.

The best-known uncertainty relation places a minimum on the product of the uncertainties (designated by Δ) in position x and momentum p—namely, $\Delta x\,\Delta p \geq \hbar/2$. Uncertainty relations are an aspect of quantum mechanics that is disconcertingly nonclassical. If, for example, a particle exists in a very specific location, its momentum must be highly uncertain and vice versa. Squeezed states are a class of quantum states that exemplify that kind of behavior, with a small uncertainty in one observable and, therefore, a large uncertainty in another.

Noisy vacuum

In addition to position and momentum, many other pairs of observables—for instance, the polarizations of light or the spin components of particles—satisfy uncertainty relations. For light, which can be treated as a quantum harmonic oscillator, the roles of position and momentum may be taken on by a pair of unitless observables, X_1 and X_2, known as quadratures. The uncertainties of those operators, ΔX_1 and ΔX_2, are governed by the uncertainty relation $\Delta X_1\,\Delta X_2 \geq 1$. In some situations, X_1 and X_2 correspond to the amplitude and phase of the electric field, and their uncertainties represent the amplitude noise and phase noise of that field.

The lowest energy state of a harmonic oscillator, called the ground or vacuum state, also has the minimum uncertainty allowed by the Heisenberg principle. Panel a of the figure, which represents the ground state of the electric field, shows the probability of measuring specific values of X_1 and X_2. As is characteristic of the ground state, measurement uncertainty is equally distributed between the two variables.

Such vacuum fluctuations exist everywhere, even in places that in a classical world would be totally dark. And they exist with every possible frequency, polarization, and direction of propagation. Their energy and field strengths are tiny, but their presence has several important physical consequences, including spontaneous emission and Casimir forces, and they limit the precision of sensitive measurements.

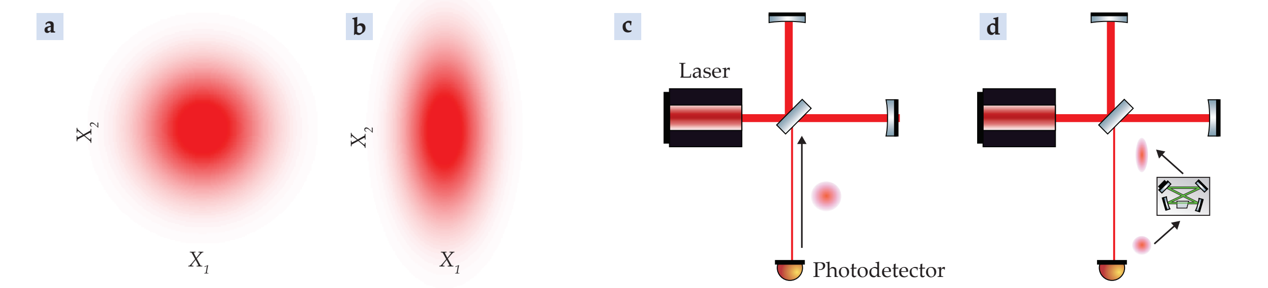
Although the uncertainty principle places a minimum on the product of the uncertainty in pairs of observables, it doesn't place any restrictions on the uncertainty in either observable alone. You can think of the uncertainty product pictorially as the area of the dark red bull's-eye in panel a of the figure. For a commonly used class of states called Gaussian states, the minimum-product requirement means that the area for the state must be at least as large as the area for the ground state. However, a state can be squeezed as in panel b to reduce the uncertainty in one observable, provided a larger uncertainty in the conjugate variable preserves or increases the area. Today researchers are using squeezed states to improve some of the most delicate measurements ever made.

So how do you actually squeeze a state? The key to any squeezing technique is to create correlations between normally independent fluctuations; such correlations can lead to the reduction of noise. Today the most widely used methods for generating squeezed states of light rely on parametric down conversion, a process in which one photon is converted into two lower-frequency photons whose phases are correlated. Squeezed states of light have also been created with optomechanical systems in which the mechanical response of a resonator to radiation pressure is used to create correlations between the amplitude and phase noise of light. Uncertainty in the direction of atomic spins can also be squeezed via measurement of light that interacts with the atoms in an optical cavity. Indeed, spin squeezing has been realized in ensembles of cold atoms and in Bose–Einstein condensates, an accomplishment that could improve the stability of atomic clocks and the performance of atom interferometers.

Detecting spacetime ripples

Gravitational waves—whether from supernovae, spinning neutron stars, or the inspirals and coalescence of compact-object binaries—distort spacetime. As a result, waves with frequencies below 10 kHz will change the length of any object they pass through. But the alterations are minuscule: The kilometer-scale interferometers currently under construction to detect gravitational waves, Advanced LIGO (Laser Interferometer Gravitational-Wave Observatory) and Advanced Virgo, will need to measure changes in their arm lengths of roughly 10^{-20} m, five orders of magnitude less than the width of a proton! The large instruments, with their 40-kg mirrors and multikilometer-long arms, are not the sort of systems normally expected to exhibit quantum behavior. However, the displacements they measure are so small that the uncertainties imposed by quantum mechanics limit their performance.

All the major Earth-based gravitational-wave interferometers are variations on the Michelson interferometer; panel c of the figure gives a schematic diagram of the device. A laser



Squeezed light and interferometry. The quantum state of light can be depicted by probability distributions such as shown in **(a)** and **(b)**. The so-called quadrature variables X_1 and X_2 here describe the electric field. Panel a gives the distribution of "vacuum fluctuations" for the ground state of the electromagnetic field; panel b gives the distribution for squeezed light. **(c)** The Michelson interferometer is the basis for Earth-based interferometers designed for detecting gravitational waves. The difference in arm lengths due to the passage of a gravitational wave is measured by monitoring the intensity of light on the photodetector shown at the bottom of the schematic. Vacuum fluctuations symbolized by the target shape enter an interferometer from the unused port (thin, red line) and cause quantum noise. **(d)** Reflections off a nonlinear cavity (inset) convert the vacuum fluctuations that would normally enter the interferometer to squeezed-vacuum fluctuations; the result is reduced quantum noise and improved measurement precision.

beam is sent down two orthogonal arms by a beamsplitter and reflected back toward the beamsplitter, where the light from the two arms interferes constructively or destructively depending on the relative length of the arms. By measuring the power at a photodetector, one can make sensitive measurements of changes in the arm lengths.

Since vacuum fluctuations propagate everywhere, they enter a Michelson interferometer from the unused port of the beamsplitter, where the photodetector is located. In 1981 Carlton Caves explained how those vacuum fluctuations cause the two types of quantum noise that limit the performance of gravitational-wave detectors: quantum radiation pressure noise, which results from fluctuations in the momentum imparted to the interferometer mirrors when light reflects off them, and shot noise, due to fluctuations in the amplitude of light arriving at the photodetector. Those distinct types of noise can be attributed to the uncertainties in X_1 and X_2. Caves suggested that the performance of a gravitational-wave detector could be improved by substituting squeezed states for the vacuum fluctuations that enter from the dark port of the interferometer.

During the past decade, members of the LIGO scientific collaboration have created sources of squeezed vacuum states suitable for integration into gravitational-wave detectors. Two gravitational-wave detectors have already used squeezed-state injection to improve their sensitivity: the GEO600 detector near Hanover, Germany, in 2010 and the LIGO detector in Washington State in 2011 (see Physics Today, November 2011, page 11). As depicted in panel d of the figure, the vacuum fluctuations that would normally enter the interferometer are first reflected off a nonlinear cavity that converts the ground-state vacuum fluctuations to squeezed vacuum fluctuations. In both the GEO and LIGO experiments, the squeezing reduced shot noise and increased the quantum radiation pressure noise; still, the quantum radiation pressure noise remained well below other limiting noise sources in the two interferometers.

For the Advanced LIGO interferometers, however, quantum radiation pressure noise will dominate in the astrophysically important 10- to 30-Hz band, so injection of squeezed states that reduce shot noise would degrade the interferometers' low-frequency sensitivity. For that reason, the Advanced LIGO instruments will include filter cavities that reduce the level of squeezing at low frequencies and preserve the high-frequency squeezing. More than 30 years after Caves made his proposal, squeezing combined with suitable filter cavities has emerged as the most practical way for Advanced LIGO to improve its sensitivity.

From thought experiment to practical tool

Squeezed states were first considered almost a century ago as theoretical constructs illustrating one of the difficult nonclassical concepts of quantum mechanics: the uncertainty principle. Once scientists created those states in the lab, they used them to test fundamental ideas of quantum mechanics. Now squeezed states are becoming a tool to improve precision measurements, to search for signals from distant astrophysical events, and to demonstrate quantum teleportation and quantum cryptography. The coming years may well see the implementation of new types of squeezed states, new methods for generating squeezed states, and further applications of squeezing to solve novel problems.

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ADDITIONAL RESOURCES

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