Squeezing the quantum noise limits

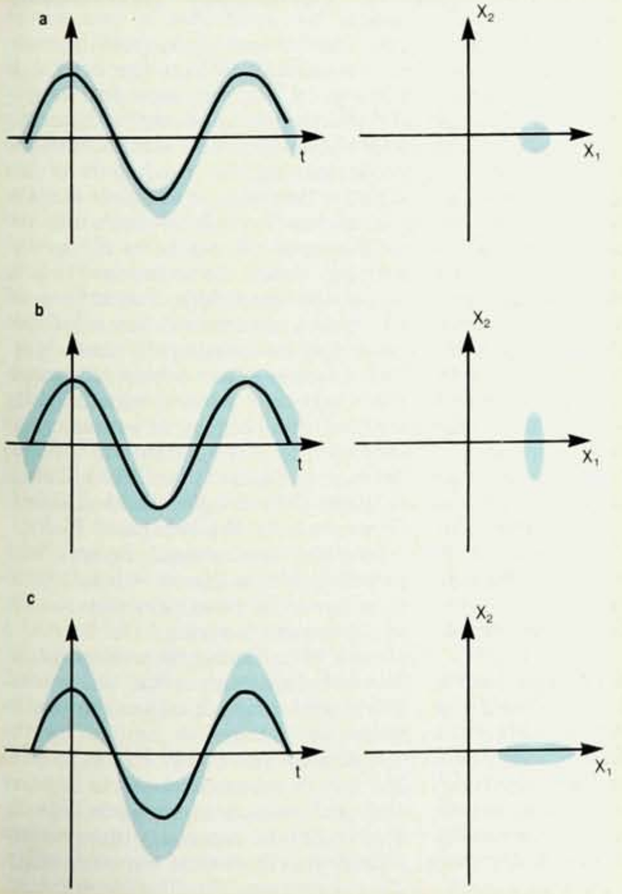
While it is true that quantum mechanics imposes strict limits on the precision of measurements, we can sometimes improve measurement precision without violating the uncertainty principle. The rub is that this improvement may be formidable to achieve in practice—and always comes at the expense of a loss in the precision of a complementary measurement. Last October a team at AT&T Bell Labs succeeded[1] in reducing the noise observed from an optical cavity below the "shot noise"—the level of fluctuations associated with variations in the vacuum fields, which is the ultimate limit to accuracy that would be predicted by semiclassical models. Although the Bell Labs experiment reduced the noise below this level by only 7 to 10%, it bolstered hopes that continued progress might eventually yield reductions in noise by factors of ten. Manipulation of the quantum noise limitations might be absolutely critical to such precision measurements as detection of gravity waves, whose faint signals are likely to be near the measurement limit of laser interferometers or mechanical oscillators. The phenomenon might possibly find applications in optical communication or optical memory systems.

The hope for noise reduction rests on the generation of so-called squeezed states. Such quantum states are best understood if one represents an oscillator (be it the electric field vectors of a light wave or the momentum or position of a mechanical oscillator) as the sum of two quadrature components whose time variations are given by sine and cosine functions, respectively. A particular mode of the electric field, for example, can be written

$$E = E_0[X_1 \cos \omega t + X_2 \sin \omega t]$$

where X_1 and X_2 are the field quadrature operators; they are complementary variables and obey an uncertainty relationship. For coherent states, these quadrature amplitudes have equal variances, and the product of these variances gives the Heisenberg minimum uncertainty $\Delta X_1 \cdot \Delta X_2 = 1/4$. These minimum and equal variances constitute, for example, the zero-point fluctuation of the vacuum state.

For a squeezed state, which is a generalization of these minimum-uncertainty states with no classical analog, the product of the quadrature variances still gives the minimum uncertainty but the variances can be unequal. Thus, noise can be reduced, or squeezed, in one term as long as it is correspondingly increased in the other. A phase-sensitive measurement should reveal a phase-dependent variation in the magnitude of the fluctuations. Carlton Caves of Caltech has depicted[2] the squeezed states as sketched in the figure on this page, where the reduced fluctuations may occur in either the amplitude or the phase.



Time variation of the electric field is shown by the black central curve in all three graphs. The colored bands indicate the uncertainty for a coherent state (**a**), and for states with reduced fluctuations in amplitude (**b**) and phase (**c**). The graphs at right show the corresponding variances in the quadrature amplitudes X_1, X_2. (From reference 2.)

To generate squeezed states of electromagnetic radiation experimentally requires phase-sensitive nonlinear techniques that couple two waves in such a way that one of the quadrature amplitudes is intensified while the other is diminished. The associated fluctuations are correspondingly enhanced or reduced. Horace Yuen of Northwestern University, whose extensive exploration[3] of the properties of squeezed states in the mid-1970s inspired the recent interest in them, stresses the two-photon nature of these states. They are generated mathematically with a Hamiltonian that contains the product of two creation operators.

Most of the current efforts to gener-

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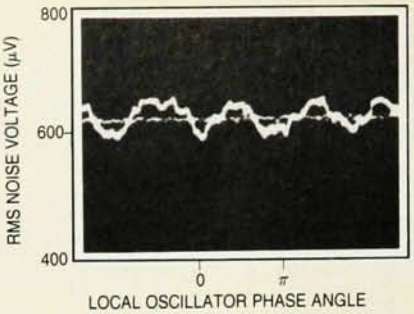
ate squeezed states make use of some form of "four-wave mixing." This technique essentially uses a medium with a nonlinear susceptibility to take some photons from two strong pump waves and feed them into two weaker beams. The nonlinear interaction establishes correlations between the photons in the weaker beams. When these two beams are then combined, the resulting light exhibits the amplified and deamplified quadrature fluctuations that characterize the squeezed states.

Yuen and Jeffrey Shapiro (MIT) first suggested[4] that degenerate, backward four-wave mixing (in which all the light waves have the same frequency and the pump beams travel in opposite directions) could be used to produce squeezed light. Margaret Reid and Daniel Walls at the University of Waikato, New Zealand, have since presented[5] a comprehensive investigation of four-wave mixing in an atomic medium with quantized fields, which considers how to minimize the noise from spontaneous emission.

Yuen and Shapiro also made the key observation that the noise from a single field quadrature could be measured with a homodyne detector. In such a detector, the squeezed light is essentially beaten against a strong local oscillator on the surface of a photodetector to yield a phase-sensitive measurement of the noise. In the balanced homodyne detection scheme used in the Bell Labs experiment, the squeezed light is combined at a 50–50 beam splitter with a local oscillator, usually derived from the pump beam itself. The waves emerging from this beam splitter shine onto two photodetectors; the output signal is the difference between the two photocurrents. The intensity fluctuations caused by the local oscillator cancel out of this difference signal, and the dominant fluctuations come from the squeezed light. As one varies the phase difference between the squeezed signal and the local oscillator, the signal becomes periodically sensitive first to one quadrature amplitude and then to the other. The noise amplitude varies accordingly.

The Bell Labs experiment was performed by Richard E. Slusher, Leo W. Hollberg, Bernard Yurke, Jerome C. Mertz and John Valley. They announced their results at the annual meeting of the Optical Society of America in Washington, DC, last October, and their results were discussed the next day at a symposium honoring Roy Glauber (Harvard), whose treatment of coherent states in the quantum theory of light laid the basis for the current work on squeezed states.

The Bell Labs experimenters used backward four-wave mixing with two counterpropagating beams from a continuous-wave ring dye laser to pump a



Homodyne rms noise voltage as a function of the phase angle between a local oscillator and the signal from a four-wave mixing cavity. With the cavity blocked, the noise level is the faint, almost flat trace associated with amplifier and vacuum fluctuations. When the cavity is open, we see the noise dipping periodically below this reference level—evidence that the vacuum has been squeezed.

beam of sodium atoms just above or below an atomic resonance. They made several important innovations. At the suggestion of Yurke, they generated the mixing in an optical cavity to enhance the gain by having the beams make many passes through the nonlinear medium. Because the mirrors differed in reflectivity, there was effectively only a single port, for both entry and exit, through which vacuum fluctuations—unwelcome additional noise—might enter. The experimenters also produced nondegenerate phase-conjugate pairs with frequencies displaced symmetrically about the pumping frequency by a multiple of the cavity frequency. By operating away from the pumping frequency, they reduced the noise from spontaneous emission.

Rather than measure the noise on an imput signal, Slusher and his colleagues looked for the squeezed state generated from the vacuum state. The fluctuations are shown in the figure on this page as a function of the local-oscillator phase angle. Every half-cycle the measured noise dips below what is measured for the amplifier and the vacuum fluctuations with the pump beam turned off.

Slusher commented to us that the drive to gain greater squeezing is a constant battle to reduce losses. For example, if the group operates closer to the atomic resonance, where the nonlinearities increase, they run into additional losses from the Lorentzian absorption tails.

Other research teams have seen indications of squeezing but have not yet achieved reproducible noise reductions below the vacuum level. At MIT, Shapiro, Prem Kumar and Mari W. Maeda have a four-wave-mixing experiment using sodium vapor as the nonlinear medium in a heat pipe rather than in an optical cavity.

At IBM's Almaden Research Lab, Marc Levenson, Robert Shelby and Stephen Perlmutter are using nondegenerate forward four-wave mixing in an optical fiber whose length (about 100 m) should allow for a far greater interaction length than the optical cavity provides. This system was expected to be free of noise. Unfortunately, Levenson said, they found differently: They discovered a new source of noise, which, while interesting in its own right, has kept them from their primary goal of generating squeezed light. This effect, which they call "guided-acoustic-wave Brillouin scattering," randomly modulates the strong pump wave and adds noise to nearby frequency bands that would otherwise be squeezed. While this acoustical noise has not disappeared (as hoped) at low temperatures, it has become small enough to yield an apparent total noise level just at the vacuum level. The IBM team is now trying an optical-fiber-ring configuration and is considering a detection scheme that will allow them to subtract the noise caused by the acoustical modes.

John Hall of the Joint Institute for Laboratory Astrophysics in Boulder, Colorado, and H. Jeffrey Kimble of the University of Texas at Austin have been trying to squeeze light by exploiting second-harmonic generation. A nonlinear crystal of KDP (potassium dihydrogen phosphate) is placed in an optical resonator that is resonant at both fundamental and second-harmonic frequencies. When the crystal is pumped by a strong wave with amplitude fluctuations, it converts the strong part of the signal to a second harmonic while leaving the weak part of the signal relatively unaffected. As the second harmonic feeds back into the fundamental, it tends to fill in the valleys. Hence the technique tends to shave the amplitude fluctuations off the peaks, decreasing the amplitude noise while increasing the phase noise. This technique can potentially generate a squeezed state of high intensity with a large degree of squeezing, as predicted by L. A. Lugiato and G. Strini (Istituto di Fisica, Milan), F. de Martini (Istituto di Fisica, Rome), M. J. Coletti (University of Waikato) and Walls.

Potential applications. Because the payoff for these heroic laboratory efforts has so far been quite slim, the era of "noise engineering," to borrow a phrase from Yurke, seems very far off. Nevertheless, physicists in several fields are looking far down the road to when they may be limited by the vacuum noise. Caves has suggested[2] the use of squeezed states to improve the performance of high-precision interferometers, especially those used to detect gravity waves (PHYSICS TODAY, February, page 17). The interferometric measurements of ultra-small displacements now planned for gravity-wave experiments are limited by the fractional error $N^{-1/2}$, where N is the number of photons detected in the interferometer's integration time. Caves has calculated that the use of squeezed states could reduce that measurement uncertainty to N^{-1}.

The measurement accuracy of interferometers is limited by two noise sources—fluctuations in the differential radiation pressure at the two mirrors and fluctuations in the number of output photons. Both types of noise are caused by the vacuum fluctuations that enter the interferometer through the unused port (the back side of the beam splitter). Each quadrature component of light entering the unused port is responsible for one of the two noise sources. Thus, if that light were squeezed, one noise source might be reduced at the expense of the other. The interferometers now planned for gravitational-wave experiments are limited by the photon-counting error. Thus Caves proposes to reduce this error by shining a squeezed vacuum state into the unused port.

Squeezed states can also be generated in mechanical oscillators designed to detect gravity waves, where they might facilitate the detection of extremely small (10^{-19} cm) perturbations of very massive (as heavy as a ton) metal bars. These displacements are on the order of the zero-point fluctuations. If experimenters can conquer some very formidable obstacles and approach this limit, they might need squeezed states to take them further.

The problem is to circumvent the restrictions that the uncertainty principle places on repeated measurements of one observable. In measuring the amplitude of harmonic oscillations of the bar, for example, one may introduce fluctuations larger than the signal to be detected. Techniques to avoid this problem have been dubbed "quantum non-demolition" measurements. One approach, termed "back-action evading measurement," is to concentrate on measurement of just one quadrature amplitude (which can be expressed in terms of position and momentum) and give up all attempts to measure the other. The very act of measurement then puts the oscillator in a squeezed state. Mark Bocko is working with David Douglass and Warren Johnson at the University of Rochester to generate mechanical squeezed states. They are planning to couple a metal bar to a transducer that senses only one quadrature amplitude of the bar's motion. Bocko told us that gravity-wave detectors might consist of two detectors, each squeezed in a different state.

A third possible application of squeezed states might be to optical communication systems. Although such states may not be able to increase the channel-carrying capacity by more than a factor of two, Shapiro and Yuen have shown that they can help to lower the error rate. Yuen commented to us that the severe loss-induced degradation is the major limit on applications of any nonclassical light. Shapiro has proposed a squeezed-state optical tap for coupling light out of a fiber with minimum loss. Such proposals must for now wait in the wings until experimenters can demonstrate noise reductions by the hoped-for factors of ten or more. —BARBARA G. LEVI

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Aladdin, fighting back, surpasses performance goals

Since the first of the year, the circulating electron beam of the Aladdin synchrotron light source at the University of Wisconsin has been surpassing 100 milliamps—its "nominal commissioning level"—and it's still getting better. This happy news must be understood in the less happy context of recent years (PHYSICS TODAY, August, page 45, and November, page 58). When construction of this roughly square electron storage ring—27 meters on a side—was begun in 1977, the goal was to achieve a stored electron beam current of at least 100 milliamps with a maximum electron energy of 1 GeV. The purpose was to provide experimenters with synchrotron light beams of adequate intensity in the spectral range from the vacuum ultraviolet up to about 4 keV in the soft-x-ray regime. This synchrotron radiation, generated as the electron beam negotiates the rounded corners of the Aladdin square, was intended eventually to be augmented by the outputs of wigglers and undulators inserted in the long straight sections of the ring.

Far from achieving the anticipated 100 milliamps, however, Aladdin had not surpassed a meager 2 or 3 milliamps of circulating electron beam current by Christmas of 1984—more than two years after its first operation. In spite of significant progress in the first half of 1985, Aladdin had still not surpassed 25 milliamps at an electron energy of 800 MeV by June, when NSF director Erich Bloch decided to terminate funding of the facility. It seemed to NSF at the time that the only serious alternative would be to spend an additional \$25 million or so on a thoroughgoing upgrade to make the storage ring, at long last, a usable synchrotron light source. And that, Bloch decided, was too much. Since October, the University of Wisconsin has been picking up the bills for the continued operation of Aladdin.

But now it all looks very different. Throughout 1985 and into this year, as the Aladdin staff have addressed the problem of trapped ions—the putative culprits—in bits and pieces, the beam current has increased in a sequence of rather spectacular improvements. The most spectacular of these increments occurred early in January of this year, when the beam current at 1-GeV electron energy reached 106 milliamps; the nominal commissioning parameters had finally been surpassed. Early in February, Aladdin was keeping four user groups happy at four separate synchrotron beam lines with an electron beam current of 135 milliamps at 800 MeV. At 108 MeV, the initial energy at which electrons are injected into the Aladdin ring nowadays, a maximum beam current of 174 milliamps has recently been achieved. This leads one to anticipate that the 800-MeV current will shortly improve again; the more circulating current one starts with at the injection energy, the more one has left after acceleration.

Trapped ions. When things go inexplicably wrong in an electron storage ring—especially at low energy—one tends to point an accusing finger at ions trapped in the beam. Residual gas atoms in the ring's vacuum chamber become ionized by collision with the circulating electron beam; the higher the current, the more ionization. Having become positively charged, these ions are now attracted to the potential well presented by the negatively charged beam.

Trapped in the beam at thermal velocities as the relativistic electrons whiz by, these ions are thought to be very disruptive. Because the mutual Coulomb repulsion of electrons in the beam is nicely canceled at relativistic velocities by their magnetostatic attraction, the Coulomb attraction of even a sparse infiltration of ions can seriously perturb the focusing of the beam. Furthermore, scattering off the lumbering ions exacerbates dispersion and loss of beam electrons. These