Hanbury Brown's steamroller

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Physics Today **61** (8), 8–9 (2008);
https://doi.org/10.1063/1.2970223

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The flagrant defiance of common sense by quantum phenomena is sometimes described as "quantum weirdness." However, phenomena that are reasonable according to the laws of classical physics but apparently defy a quantum explanation are also possible; perhaps those should be labeled "anti-weird." The Hanbury Brown and Twiss effect would be a prime example of anti-weirdness: Its explanation in the language of classical waves was straightforward, but the phenomenon appeared to defy quantum physics, at least at first. Arguments over its quantum description generated a rancorous—though ultimately fruitful—debate: The discovery of the HBT effect launched the field of quantum optics.[1] Although the effect was discovered during an attempt to create a tool for astronomy, its most useful applications turned out to be in nuclear and heavy-ion physics and, most recently, ultracold atom physics.

The history of the HBT effect is a colorful story of inspiration, dismay, controversy, and ultimate success.[2] Robert Hanbury Brown was a young radar engineer who came of age during World War II and was at loose ends in 1949 when he wandered into the orbit of Bernard Lovell at the Jodrell Bank radio observatory near Manchester, UK. Radio astronomy was in its infancy, and there was serious confusion about whether certain prominent radio emitters were starlike or extended. Hanbury became obsessed by the challenge of measuring their angular sizes. In principle, the task was straightforward: The source is observed with two radio dish antennas whose signals are brought together through transmission lines and added. The system is actually a giant radio-frequency phase interferometer. As the antennas are moved apart, the signals add constructively or destructively, creating an interference pattern that eventually fades. The angular diameter of the source is essentially the ratio of the wavelength to the distance where interference fades. The only problem was that for starlike radio sources, the dishes would need to be separated by thousands of kilometers. The transmission lines, assuming that they were available across the oceans, would introduce so much phase noise that any interference signal would be wiped out.

From long hours of staring at cathode-ray tubes that displayed signals from astronomical radio sources, Hanbury knew that the signals looked merely like noise. Although noise is usually regarded as an experimental nuisance, in a sudden insight, he realized that noise could solve his problem. The random cathode-ray-tube patterns from two nearby antennas would look identical, which is to say that the noise would be correlated, but if the antenna separation were increased, the correlations would disappear. The angular size of the source would be approximately the ratio of the wavelength of the signal to the distance at which the correlations were lost. The beauty of the method is that noise fluctuations can easily be compared over cable or radio, or even stored on tapes for later comparison.

Hanbury built an "intensity interferometer," a system that measured noise correlations of the signals (the average of their product) using a portable and a fixed radio dish antenna. By observing the correlations as he moved the portable dish across the countryside, he explored radio sources in Cygnus and Cassiopeia. To his chagrin, they turned out to be so large that a simple, ordinary phase interferometer would have worked like a charm. As he wryly described the experience, he had spent two years "building a steamroller to crack a nut."[2] Hanbury, however, was relentlessly enthusiastic. He immediately set about applying his idea to optical astronomy.

Hanbury's method involved recording the fluctuating intensities of signals that are received by two radio dishes looking at the same noise source but that can arrive at slightly different times due to the different paths to the dishes. One then computes the ratio of the time average of the product of the intensity fluctuations to the product of the time-averaged individual intensity fluctuations—a quantity known as the intensity correlation function.[2] As the dishes are moved apart, under ideal conditions the correlation function drops from two to one. The angular size of the source is approximately the ratio of the wavelength to the distance at which the correlation function decreases significantly.

A brouhaha narrowly averted

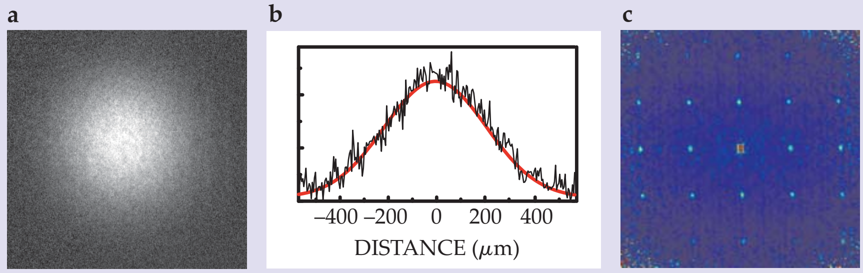
Hanbury employed a wave-based analysis that fails at optical frequencies where one must detect individual photons. He called on Richard Twiss, a mathematician, to help work out the theory for photons. They concluded that if one observed light from a star using two nearby phototubes, the phototubes would tend to click simultaneously. They argued that the correlation function for the phototube signals would behave just as it would for the radio-wave signals. Critics argued that such behavior was impossible: A single photon could be detected at one detector or the other, but not both. Furthermore, because photons from stars are emitted randomly, the arrival of one photon at one detector could not possibly influence the arrival of a second photon at a different detector.

Hanbury Brown and Twiss's proposal generated such a heated debate that they decided to settle the matter by a tabletop demonstration. Although they managed to see a small effect, two other groups failed to find it. The theoretical and experimental dispute became so lively that a brouhaha almost broke out. Fortunately, Edward Purcell calmed the situation by demonstrating that the HBT effect has a straightforward explanation in either a classical or a quantum mechanical picture. In addition, he showed that the groups that could not see it had failed to appreciate that the long response time of their correlators, compared with the short correlation time of broadband optical sources, would preclude observing it.[3] Today the HBT effect is often explained simply as the enhancement that occurs in observing identical bosonic particles. The same argument, when applied to fermionic particles, predicts a decrease in two-particle correlations.

Hanbury went on to a distinguished career in radio astronomy, although ironically the effect for which he is best known was never particularly important for astronomy. The reason is that in practice, intensity interferometry is much less sensitive than phase interferometry. At radio wavelengths, the advent of atomic frequency standards made very long baseline phase interferometry practical by providing local reference signals with which to record the phase of a signal at each radio telescope, even if the telescopes are on separate continents. In the optical regime, phase interferometry requires distances to be held constant within a fraction of a wavelength. Formerly, that constancy required heroic measures; today, laser metrology makes it practical.

Two-particle correlations can be used to measure the size of any structure that emits particles randomly, provided that individual particles can be detected. For instance, the size and structure of heavy nuclei that radiate pions in high-energy nuclear collisions have been found from two-particle correlations.[4]

Somewhat unexpectedly, the HBT effect eventually found a new career at the ultracold end of the energy scale, where it has turned out to be an exquisite tool for exploring the physics of quantum gases. Until the advent of ultracold atoms, the correlation time for atoms was too short for the HBT effect to be detectable. The HBT effect in atoms was first observed with ultracold metastable neon[5] and later measured with impressive precision with metastable helium-4.[6] The opposite effect—the depression of the correlation function at short times—has also been observed, using metastable helium-3, which obeys Fermi statistics.[6]



Noise correlation spectroscopy. (a) Photograph of a gas of about 5 X 10^5 rubidium-87 atoms a few milliseconds after being released from a trap. **(b)** Column density (arbitrary units) in a plane through the center of the trap. The fluctuations around the smooth calculated curve look typical of experimental noise. **(c)** Second-order correlations in the noise fluctuations. The periodic points reveal that the source was structured. (Adapted from ref. 7, courtesy of Simon Fölling.)

What the noise knows

Although the terms "Hanbury Brown and Twiss effect" and "two-particle correlations" are often used synonymously, Hanbury's seminal idea came from watching noise patterns on a cathode-ray tube created by huge numbers of photons that generated flickering photocurrents. The signal looked like classical noise and had nothing to do with two-particle correlations. The spirit of Hanbury's original inspiration to look at noise is reasserting itself. Using two radio dishes, Hanbury could aspire to measure the size of a source from intensity correlations but could learn little else about it. Today, using arrays of CCD detectors rather than a single pair of phototubes, one can make millions of measurements simultaneously, which enormously increases the resolution of noise interferometry. The raw signals look like noise, but the correlations hidden in the noise can reveal a detailed picture of the source.

The figure gives an inkling of the power of noise interferometry.[7] It was taken with a CCD detector array using about 100 000 pixels. Panel a is the image of a cloud of ultracold atoms taken a few milliseconds after they were released from a magnetic trap. (Before release, the sample was too small to be photographed.) The atoms, having flown out with the random speeds of a thermal distribution, display a Gaussian density profile. The drawing in panel b is a plot of the data superimposed on the smooth curve of the calculated distribution. The fluctuations look like typical experimental noise, but their second-order correlations contain hidden information, as panel c shows. The second-order correlation function was found by multiplying the fluctuation from each pixel of the array by the fluctuation at every neighboring point. The regular peaks reveal that the density has structure. The atoms were initially confined in an optical lattice—a configuration of standing waves that creates a regular pattern of optical traps. The imprint of that structure is clearly visible in the density correlations.

A new world of many-body physics was created by the advent of ultracold atoms. Noise spectroscopy has suddenly acquired renewed interest because it seems to be perfectly suited to this new world. For instance, Ehud Altman, Eugene Demler, and Mikhail Lukin have pointed out that noise spectroscopy is an excellent tool for studying pairing symmetry in superfluidity, the transition of molecular gases from Bose–Einstein condensation to the Bardeen-Cooper-Schrieffer regime, spin correlations in multicomponent boson systems, and many other phenomena.[8] In short, noise spectroscopy has a gold mine of opportunities. It appears that Robert Hanbury Brown's steamroller is finally finding objects worthy of its power and applications more interesting than cracking peanuts.

I thank Simon Fölling for helpful comments.

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