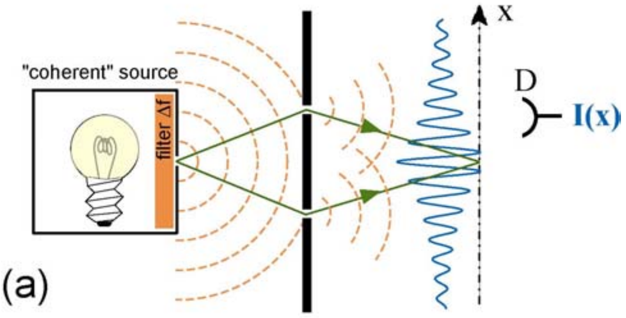
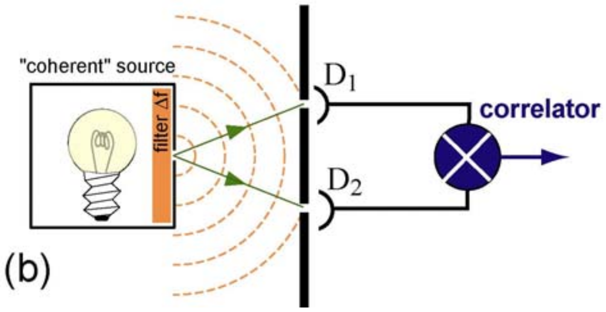
by Cristian Schönenberger, Jan. 2003

From photon bunching to electron antibunching

Any (coherent) wave, if split into two partial waves (two beams) is able to produce periodic intensity variations in a region where the two beams intersect each other. An apparatus that splits the incident beam and brings the two partial waves to cross is called an interferometer. The observed intensity pattern is known as the interference pattern. Its observation requires a sufficiently coherent source. The number of observed interference fringes is a measure of the degree of coherence. An incident spherical wave, originating from a localized point in space with a given fixed frequency would have infinite coherence. Such an ideal wave only exist in textbooks. Real waves are never perfect, because real sources have a finite extent and emit within a finite frequency band.





A prototype interferometer is the Young's double slit apparatus, shown in illustration (a). If a small light source emitting in a narrow frequency band Δf is placed in front of this apparatus, an interference pattern is observed at the observation screen, i.e. the intensity $I(x)$ as a function of coordinate x changes from large (constructive -) to small (destructive interference) in a periodic manner.

What I have described here is widely known and taught undergraduates. Unfortunately, what is less well known is the fact that coherence can also be probed by simply placing *two* detectors right behind the two holes of Young's apparatus and recording the respective intensities time-resolved. This is shown in illustration (b). This holds true, despite that there is no (obvious) region of interference. What I have drawn in (b) is one variant of an experimental setup invented half a century ago by Hanbury-Brown and Twiss (HBT) (R. Hanbury-Brown and R. Q. Twiss, Nature **177**, 27 (1956)). Hanbury-Brown and Twiss actually applied this setup to measure the size of the star Sirius, by determining the coherence of the star's light field using two spatially separated telescopes (R. Hanbury-Brown and R. Q. Twiss, Phil. Mag. **45**, 663 (1954)). The HBT experiment is a *key* experiment in physics, not because it just replaces an interferometer, but because the outcome of the experiment was quite different than anticipated.

A light source is thought to emit photons and a detector responds with a “click” to a single photon. In an HBT experiment we measure the rate of coincidence r_C, i.e. the probability that both detectors click simultaneously normalized by the product of the two probabilities of detecting photons in either detector. HBT thought they could prove the existence of photons as particles. If the light would be composed of fundamental particles that cannot be split into two, each particle would be detected in either detector, hence r_C was expected to be zero (no coincidence). For convenience we define a correlation parameter C by subtracting 1 from r_C. Hence, C was expected to be -1. To their surprise, HBT found C to be positive! To understand the impact of this result, we mention that $C = 0$, if the two detectors click fully randomly in an uncorrelated fashion. A positive C therefore tells that if we detect a photon in, say detector D_1, we know that the probability that detector D_2 also has recorded a click is larger than the average probability of photon detection. These a first sight strange correlations must arise in the photon source, which obviously needs to emit at least two photons simultaneously. That a light source can emit many photons virtually at the same instant is no surprise. But only photons originating from the same coherence volume can give rise to correlations. Such photons are indistinguishable particles (if for simplicity we assume that they have identical polarization) and must therefore obey the rules of quantum mechanics. Because photons are bosons, quantum mechanics allows for many photons to occupy the same state, leading to the observed positive correlations. A photon source giving rise to positive correlations $C > 0$ in an HBT experiment is said to display bunching. It is as if the light is emitted in bunches of photons. Bunching is observed for a thermal light source whose light field follows Bose-Einstein statistics. In retrospect the experiment of Hanbury-Brown and Twiss was a failure, but it started a whole new branch of physics, i.e. quantum optics. The observed bunching can actually be seen as a sign of wave-like behavior. It is amusing to mention that a laser generates the most random outcome possible (i.e. $C = 0$), although it is the most coherent source of light.

What about fermions? It was very early recognized that quantum statistics would enforce a negative C in an HBT experiment performed with a beam of fermions, for example electrons. It is the Pauli principle that prohibits indistinguishable fermions to occupy the same state. This leads to anticorrelations or antibunching behavior. Though this was recognized long ago, it proved very hard to realize such an experiment. The reason is that free electron beams are rather dilute and compared to today's light sources everything else than coherent.

It is quite an impressive achievement that this experiment has been realized recently. The first two results (University of Basel and Stanford University) made use of semiconducting nanostructures in which a beam of highly degenerate fermions and electronic beam-splitters can easily be implemented (M. Henny *et al.* and W. D. Oliver *et al.*, Science **284**, 296 and 299 (1998)). Both results yield $C = -1$, i.e. full anticorrelation. In a free electron-beam, this experiment is much harder. However, Harald Kiesel and coworkers from the Institut für Angewandte Physik at the University of Tübingen have observed Hanbury Brown-Twiss *anti*-correlations very recently (H. Kiesel *et al.*, Nature **418**, 392 (2002)). Their setup corresponds to illustration (b) with the source being a cold tungsten field emitter. Because the degeneracy of the free beam of electrons is low, the measured anticorrelation is small. C is of order -10^{-3} in their experiment. Though the observed effect is small, it is significant and clearly negative. The present experimental results are great achievements and it required extraordinary skills to meet this challenge. Remember, this is an experiment which has been discussed for decades (see for example: M. P. Silverman Phys. Lett. A **120**,442 (1987)).

Today, we have a much deeper understanding of Hanbury-Brown & Twiss correlations. Photon sources have been built, so called single-photon sources, that display full anticorrelation -- loosely speaking, behave as electrons. Here, photons do what Hanbury-Brown & Twiss thought they would do in general. The story is not yet finished, since if we can make photons to behave as electrons, why not doing the reversed. This is indeed possible, at least in principle, for example, if the electrons are emitted as spin-entangled pairs. Can we realize it? Future will tell!