Electrons antibunch

Hanbury Brown & Twiss anticorrelations have been observed for free fermions

From **Christian Schönenberger at the Institute of Physics, University of Basel, Basel, Switzerland**

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, guided by e.g. mirrors, 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, emitting the wave incident to the interferometer. 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, e.g. for a light bulb from red to blue. A prototype interferometer is the Young's double slit (or double hole) 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 as a function of coordinate x changes from large (constructive interference) 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 (regions where partial waves overlap).

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 1956 *Nature* **177** 27). 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 1954 *Phil. Mag.* **45** 663). 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 initially anticipated.

A light source is thought to emit photons and a detector can respond with a 'click' to a single photon. What is actually measured in a HBT experiment is 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 detector 1 and 2. Since photons are fundamental particles that cannot be split into two, r_C was expected to be zero. 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 us 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 a 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 a HBT experiment is also 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. It is however not observed for a laser, whose field is determined by Poisson statistics.

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 behaviour. 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 very recently. Harald Kiesel and coworkers from the Institut für Angewandte Physik at the University of Tübingen have observed Hanbury Brown-Twiss *anti*-correlations in a beam of free electrons (H. Hiesel *et al.* 2002 *Nature* **418** 392). There 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, too. C is of order -10^{-3} in their experiment. Though the observed effect is small, it is significant and clearly negative. Three years before, antibunching of electrons was observed in semiconducting nanostructures, in which a beam of highly degenerate fermions can easily be generated (M. Henny *et al.* and W. D. Oliver *et al.* 1998 *Science* **284** 296 and 299, respectively). The present experiment is a great achievement 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 1987 *Phys. Lett. A* **120** 442).

Now that the Hanbury Brown & Twiss experiment has demonstrated bunching and antibunching, has been performed for bosons *and* fermions, it would be time that we are going to teach it to our undergraduates. HBT is as beautiful as the Young's double slit interferometer. It had an important impact on physics, as it may be considered the seed out of which quantum optics flourished into a fascinating discipline of physics.

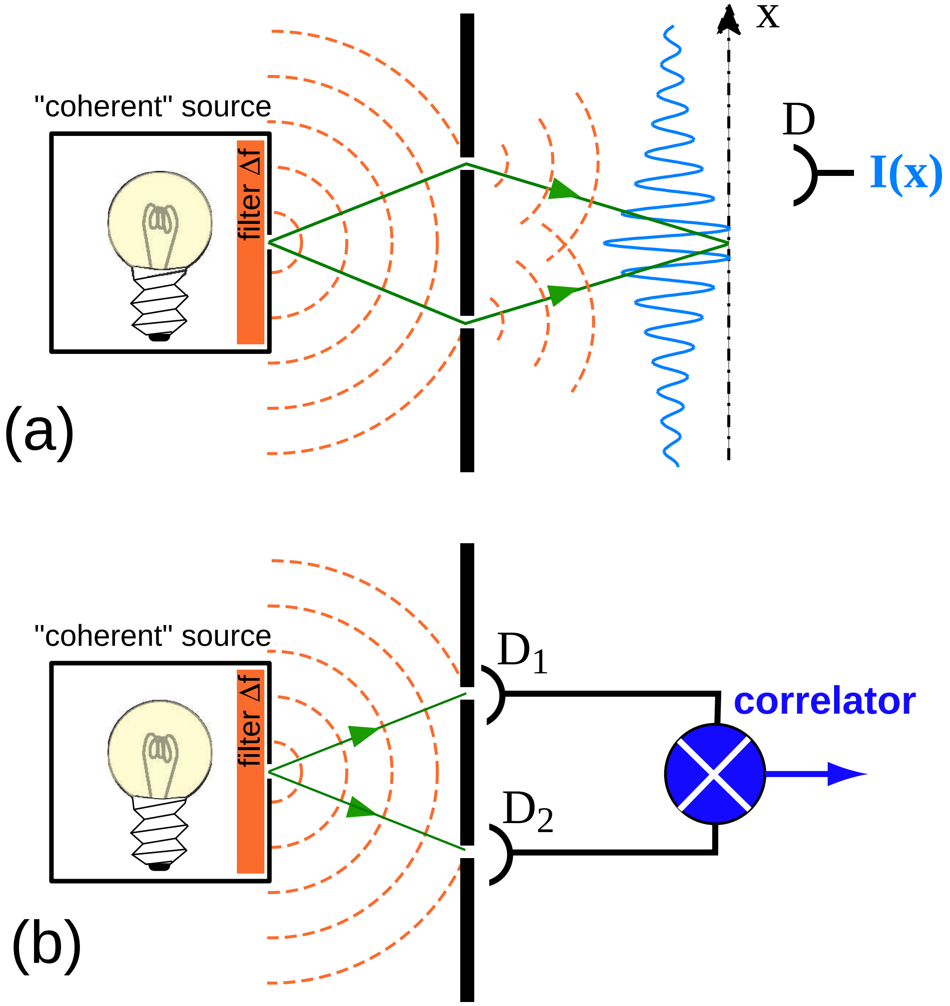

Figure 1: (a) Young's double slit interferometer. The superposition of the two partial waves (green) leads to a periodic intensity pattern (blue), called interference fringes. The number of visible fringes is a measure of the coherence of the source. (b) The coherence of a source can also be determined in a Hanbury Brown & Twiss setup, by evaluating the correlation of measured counts in *two* detectors, placed right behind the two slits. If there are positive/negative correlations (enhanced/suppressed coincidence), the source is said to display bunching/antibunching behavior. Bose-Einstein statistics enforces bunching in a thermal light source, while Fermi-Dirac statistics leads to antibunching for a coherent source of electrons.