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Quantum interference in time

Bosons—especially photons—have a natural tendency to clump together. In 1987, three physicists conducted a remarkable experiment demonstrating this clustering property, known as the Hong–Ou–Mandel effect. Recently, researchers at ULB's Centre for Quantum Information and Communication, have identified another way in which photons manifest their propensity to stick together. This research has just been published in *PNAS*.

Since the very beginning of quantum physics, a hundred years ago, it has been known that all particles in the universe fall into two categories: fermions and bosons. For instance, the protons found in atomic nuclei are fermions, while bosons include photons—which are particles of light—as well as the Brout-Englert-Higgs boson, for which François Englert, a professor at ULB, was awarded a Nobel Prize in Physics in 2013.

Bosons—especially photons—have a natural tendency to clump together. One of the most remarkable experiments that demonstrated photons' tendency to coalesce was conducted in 1987, when three physicists identified an effect that was since named after them: the Hong–Ou–Mandel effect. If two photons are sent simultaneously, each towards a different side of a beam splitter—a sort of semi-transparent mirror—, one could expect that each photon will be either reflected or transmitted. Logically, photons should sometimes be detected on opposite sides of this mirror, which would happen if both are reflected or if both are transmitted. However, the experiment has shown that this never actually happens: the two photons always end up on the same side of the mirror, as though they 'preferred' sticking together!

In an article published recently in US journal *Proceedings of the National Academy of Sciences*, **Nicolas Cerf—a professor at the Centre for Quantum Information and Communication (École polytechnique de Bruxelles)**—and his former PhD student Michael Jabbour—now a postdoctoral researcher at the University of Cambridge—describe how they identified another way in which photons manifest their tendency to stay together. Instead of a semi-transparent mirror, the researchers used an optical amplifier, called an active component because it produces new photons. They were able to demonstrate the existence of an effect similar to the Hong–Ou–Mandel effect, but which in this case captures a new form of quantum interference.

Quantum physics tells us that the Hong–Ou–Mandel effect is a consequence of the interference phenomenon, coupled with the fact that both photons are absolutely identical. This means it is impossible to distinguish the trajectory in which both photons were reflected off the mirror on the one hand, and the trajectory in which both were transmitted through the mirror on the other hand; it is fundamentally impossible to tell the photons apart. The remarkable consequence of this is that both trajectories cancel each other out! As a result, the two photons are never observed on the two opposite sides of the mirror. This property of photons is quite elusive: if they were tiny balls, identical in every way, both of these trajectories could very well be observed. As is often the case, quantum physics is at odds with our classical intuition.

The two researchers from ULB and the University of Cambridge have demonstrated that the impossibility to differentiate the photons emitted by an optical amplifier produces an effect that may be even more surprising. Fundamentally, the interference that occurs on a semi-transparent mirror stems from the fact that if we imagine switching the two photons on either sides of the mirror, the resulting configuration is exactly identical. With an optical amplifier, on the other hand, the effect identified by Cerf and Jabbour must be understood by looking at photon exchanges not through space, but through time.

When two photons are sent into an optical amplifier, they can simply pass through unaffected. However, an optical amplifier can also produce (or destroy) a pair of twin photons: so another possibility is that both photons are eliminated and a new pair is created. In principle, it should be possible to tell which scenario has occurred based on whether the two photons exiting the optical amplifier are identical to those that were sent in. If it were possible to tell the pairs of photons apart, then the trajectories would be different and there would be no quantum effect. However, the researchers have found that the fundamental impossibility of telling photons apart in time (in other words, it is impossible to know whether they have been replaced inside the optical amplifier) completely eliminates the possibility itself of observing a pair of photons exiting the amplifier. This means the researchers have indeed identified a quantum interference phenomenon that occurs through time. Hopefully, an experiment will eventually confirm this fascinating prediction!

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