Landmark Experiment with light delves into mysteries of Quantum Physics

At the start of the 19th century (ca. 1801), the English scientist Thomas Young was the first to record one of the most famous experiments in optics - and all of science - known as the "double slit" experiment.

Thomas Young's double slit experiment demonstrates that light is a wave phenomenon. As the waves pass through the slits they fan out and interfere with each other to produce an interference pattern on the photographic film. This patterns reveals constructive and destructive interference. (Credit: The Most Beautiful Experiment; Kelly Neill.)

At first, it was taken to confirm that light is fundamentally a kind of wave - like the ripples that move across the surface of a pond after you toss a pebble into it.

In the 20th century, a new idea took hold: That light exhibits the characteristics of an electromagnetic wave, but is also observed as a stream of individual particles or packets of energy, called "photons". This hypothesis is known as "wave-particle duality". It's at the very heart of quantum mechanics - a new kind of physics that had Albert Einstein (of all people) scratching his head in puzzlement and disbelief. (Einstein: If there were bubble gum trading cards for scientists ...)

Recently, at a university lab in France, a team led by scientists from France and China reprised the quantum version of the double slit experiment and gave it a dramatic new twist. Using state-of-the-art optical and electronic instrumentation, they performed a kind of double slit experiment that was first proposed by a scientist named John Wheeler almost 30 years ago. And with this new level of experimental perfection, they eliminated both the "relativistic" loophole and another strange sounding idea called "spooky action at a distance" - but left intact an even stranger sounding possibility called "retroactive causality".

If you're ready to leave this post in a huff (if you can find one) I could hardly fault you. But feel free to peruse the latest tedious, self-congratulatory tagline (italicized text) at the very end of this post before you move on to the next one. The taglines are always complimentary. Otherwise, read on ...

Towards the end of the 20th century a new version of the double slit experiment became technically feasible: The **quantum** double slit experiment. It is possible to fire just one unit of light - a single photon - towards the double slit apparatus. Light can be fired at the apparatus as a series of one photon after another - and each photon can be registered individually as it passes through the apparatus.

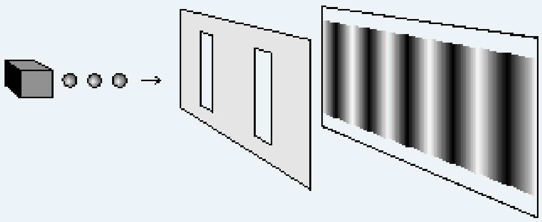
Consider a photo detector array (i.e. the "film" in a digital camera) placed behind the double slit apparatus. If Z is designated as the axis from the photon gun towards and perpendicular to the plane of the detector array (i.e. the axis along which the photons travel towards the apparatus) then the detector array records the XY position of each photon when it arrives. But it does not resolve which of the two slits the photon passed through to reach the detector array.

The photo detector array serves exactly the same purpose as the old fashioned photographic film in the 19th century apparatus: Instead of having to insert unexposed film to start recording a new experiment, the photo detector array is zeroed or reset to its unexposed condition.

Remark this setup as "Experiment A".

What are the results?

The wave interference pattern emerges. As photon after photon is recorded, the image that emerges is the same pattern of alternating light and dark bands that was recorded on photographic film in the earlier (i.e. non-quantum) experiment at the very top of this post. The same pattern of constructive and destructive interference as pictured in the diagram (again) at the very top of this post.



Experiment A: The wave interference pattern emerges as photons arrive at the photo detector array behind the double slit apparatus.

This is remarkable. As single photons are arriving one after another, at very discrete intervals, what could produce an interference pattern? It's as if every photon passes through both slits at the same time and interferes with itself at the XY plane of the recording device.

Experiment A: Where it says "particle", think "photon" ... the interference pattern leads us to conclude that the photon has passed through both slits! In the counterintuitive logic of quantum mechanics, the photon has also passed through only the slit on the left, only the slit on the right, and not passed through either slit. Image: University of Michigan.

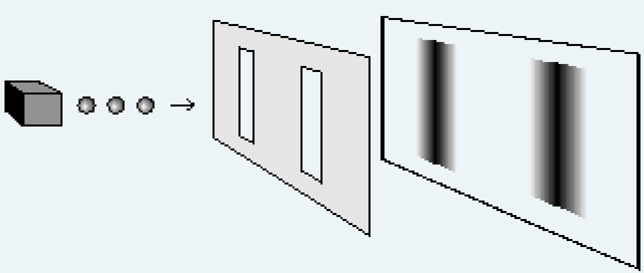
Now add something to the experiment: A photo detector that can determine when a photon passes through a slit. All that is required is one such photo detector at either one of the slits. It's a theoretical kind of detector that senses the photon without "damaging" it or stopping or deflecting its path.

It is not physically possible to have such a detector, but with some clever "sleight of hand", it is possible to set up a laboratory experiment that works exactly like this.

Remark this setup as "Experiment B".

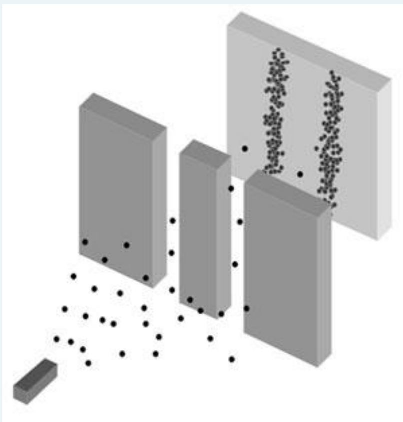
And what are the results this time?

Remarkable again. The interference pattern is eliminated - completely. What's recorded at the "camera" behind the double slit apparatus are just two discretely separated bands - each exactly in line with one of the slits.

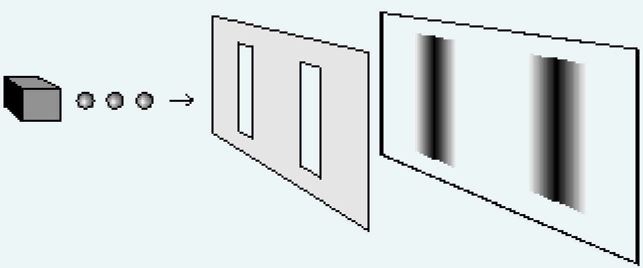


Experiment B: An additional photo detector at either one of the slits records when an experiment photon passes through that slit.

When the apparatus is set up to run Experiment B - with a photo detector at one of the slits - the photons behave like particles instead of waves. Each photon passes through either one slit or the other, but never through both at the same time. It's like a rifle range, and just in front of the paper target is a thick layer of steel with two closely spaced slits, each slit wide enough to let through a bullet. If you fire enough times you could put about an equal number of bullets through each slit, and when you remove the paper target, there will be two bands in it, one behind each slit. But there will not be a pattern of regularly spaced interference bands.



Rifle range: Before the bullets reach the target, they must pass through a thick steel plate with two slits. If bullets go through the slits they will most likely land directly behind the slit, but if they come in at a slight angle, they will land slightly to the sides. The resulting pattern is a map of the likelihood of a bullet landing at each point. In other words ...



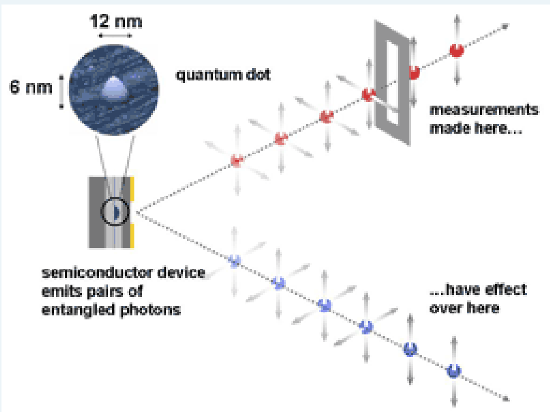
Experiment B: The photons are behaving like particles instead of waves ... images courtesy of Department of Mathematics at the University of Munich and Black Light Power, Inc.

I found a perfect five minute YouTube video with "Dr. Quantum" that illustrates all this using a very simple animation with voiceover. The video illustrates an experiment with electrons - but if every time you hear "electron", you think "photon" - every facet of the video carries over 100 percent from electrons to photons.

How can photons behave in this apparently "schizophrenic" way? It seems far-fetched, but what if the photon has some way of "knowing" whether the double slit apparatus is configured as Experiment A, or as Experiment B, with the addition of the photo detector at one of the slits? What if there is some unknown signal or connection between the photon and the apparatus? Or between the photon and whatever goes on in the scientist's mind when he (she) decides to run either Experiment A or Experiment B?

It could be that the configuraton of the apparatus (A vs. B) is propagated to the photon by a process that takes time - a process possibly as fast as the speed of light - but not any faster. This would be the "relativistic" loophole - a reference to Einstein's Special Theory of Relativity.

It could be that the configuration of the apparatus (A vs. B) is propagated to the photon by a process that is literally instantaneous. This would be an example of "spooky action at a distance".



Spooky action at a distance: The diagram demonstrates a pair of photons that are in a state of quantum entanglement. It has been demonstrated that an observation performed on one photon - in this example, a measurement that reverses its spin polarization - instantaneously reverses the spin polarization of the other photon. Remarkably, there is credible experimental evidence to indicate that "spooky action" (i.e. quantum entanglement) has been confirmed when the photons are separated by as much as 144 kilometers - the distance between the Canary Islands of La Palma and Tenerife. Since the effect is literally instantaneous, it is also called a "superluminal" effect (i.e. faster than light). Image: Toshiba Research Europe.

John Wheeler proposed his 1978 thought experiment to determine, once and for all, whether photons in the famous "double slit" experiment can in some way infer the presence of an observer before they are emitted. The image above shows the single photon source (pumped by a green laser) that Jean-François Roch and colleagues from the École Normale Supérieure de Cachan used in their faithful version of Wheeler's experiment. Photo credit: Vincent Jacques; PhysicsWeb.

The genius of the most recent experiment in France was to set up the experiment in such a way that the photon has already entered the front end of an interferometer that is the experimental equivalent of a double slit apparatus - and then have a method, downstream in time, for the equipment to automatically configure itself as Experiment A or Experiment B in a truly random way: A "delayed choice" experiment as Wheeler had visualized. The French team developed a method of switching that is fast enough, and that provides enough physical separation between the front end of the interferometer and the random generating device, that both the "relativistic" loophole, and also the "spooky action at a distance" loophole, are eliminated as theoretical possibilities.

In the French experiment, the random generator is synchronized with the entry of the photon into the front end of the interferometer, which assures that the photon enters the future light cone of the random choice at about 24 meters (80 nanoseconds) downstream from the front end of the interferometer, thus closing or eliminating the "relativistic loophole".

The photon travels 48 meters (160 nanoseconds) downstream from the front end of the interferometer before arriving at the photo detectors that provide the measurement that characterizes its behavior as either "wave" or "particle".

Remarkably, the results are as before: Experiment A produces the electromagnetic wave interference pattern. Experiment B produces the two particle impact bands or "bullet holes". To paraphrase the conclusion of a brief report in ScienceNOW: