

## Wave-particle duality of light. II.

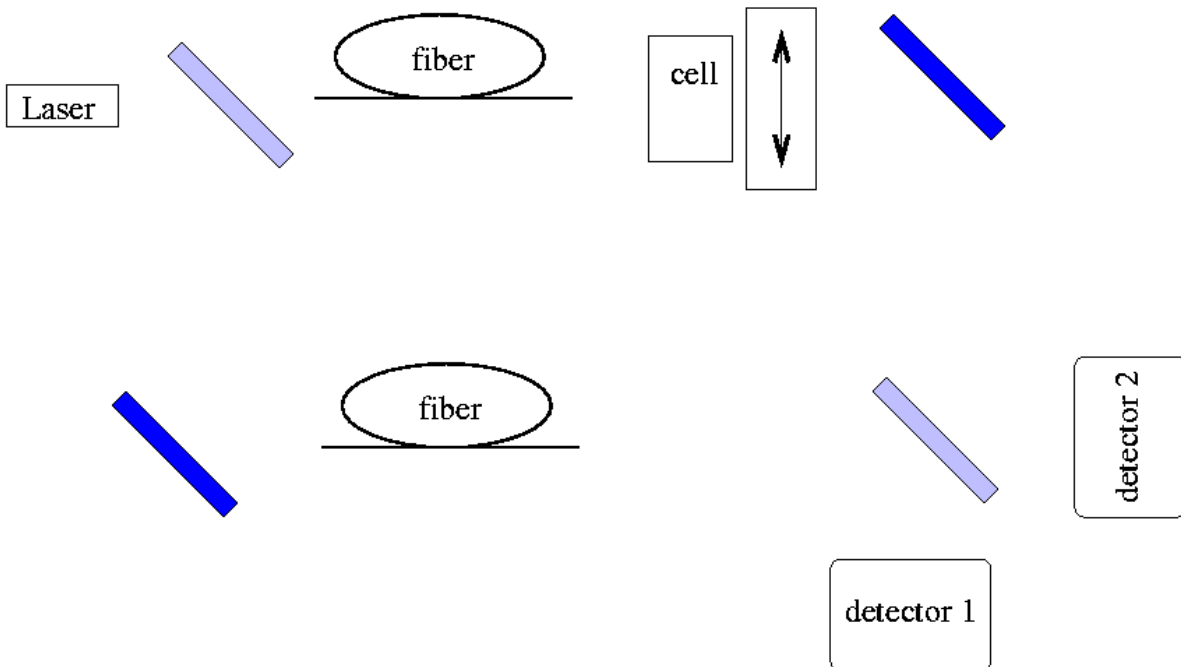
Light can apparently behave like a particle, or like a wave? But under certain circumstances, it must somehow behave like both at once.

One of the first experiments of this sort was described by Hellmuth, Walther, Zajonc and Schleich, in *Physical Review A*, vol 35, p. 2532 (1987). The scanned results and conclusion from that paper are shown below. A slightly earlier paper by Alley et al., in *Proceedings of the International Symposium on Foundations of Quantum Mechanics*, (Tokyo, 1986), describes a very similar experiment, but is much harder to find.

The basic idea of the experiment is to set up an interferometer with two legs. Each leg has a loop of optical fiber about 5 meters long.

Q: How long will it take a ray of light to pass through the fiber?

One of the legs also has a "Pockells cell", which acts like a piece of polarizer, followed by a second polarizer. The Pockells cell can be switched from one polarization state to another very quickly -- in about 4 ns.



The blue rectangles in the diagram above represent mirrors. The solid blue ones are ordinary mirrors which reflect 100% of the light striking them; the light blue ones are

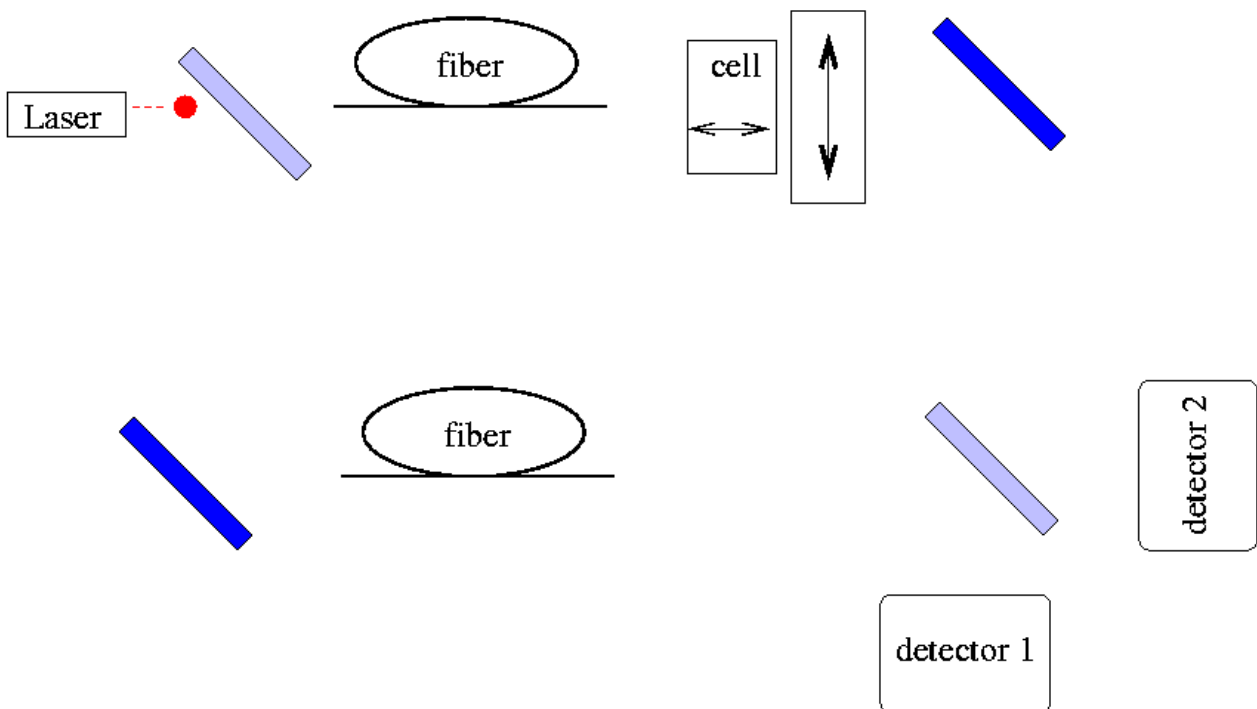
"half-silvered" mirrors, also called "beam splitters", which reflect 50% of the light and transmit the other 50%.

### If light is a photon ....

Now, let's consider what happens if light is composed of discrete pieces: photons. We have a couple of photodetectors at the end of the photometer -- what will they read when we send a pulse of light out of the laser?

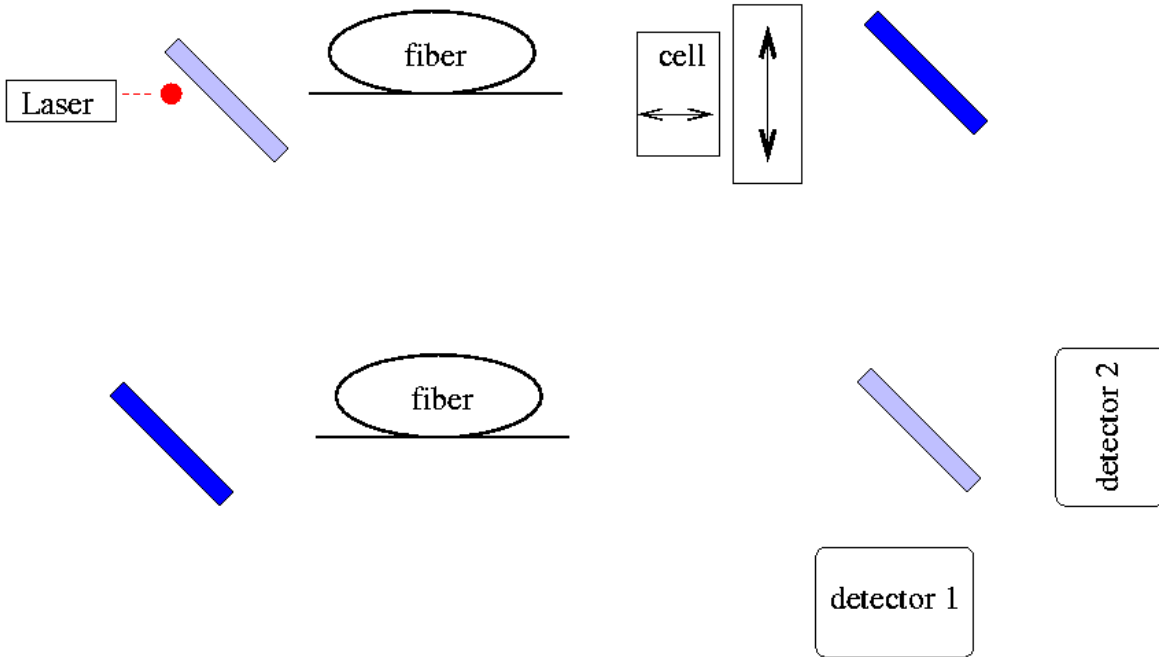
Suppose we set the Pockells cell so that it only allows horizontally polarized light to pass through it. This effectively "closes" the upper arm of the interferometer, because any photon passing through the cell will immediately be blocked by the fixed polarizer behind it.

*Click on the picture below, or any picture with a box around it, to view an animation.*

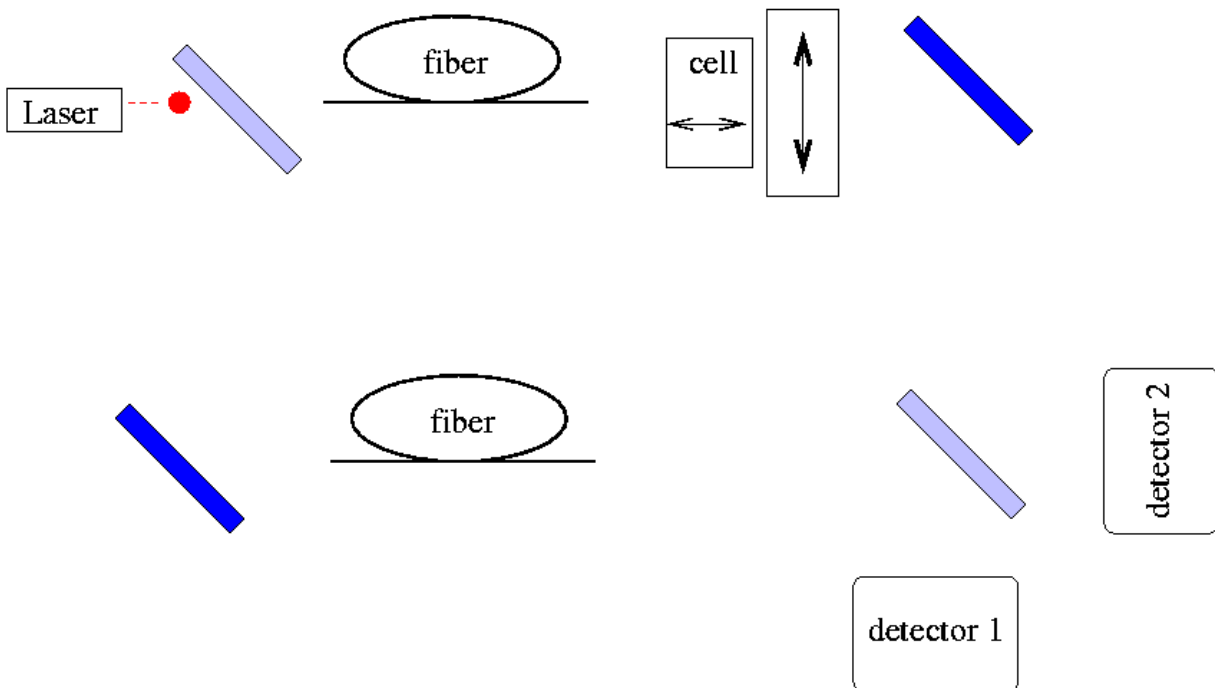


Since 50% of the photons from the laser will pass through the first beam splitter, we expect that 50% of the time, both the detectors will read 0.

On the other hand, 50% of the time, the photon will bounce off the first beam splitter and head towards the lower leg. What will happen then? Well, half of the time (25% overall), the photon will pass through the second beam splitter and into Detector 2.



The other half of the time (25% overall), the photon will bounce off the second beam splitter and into Detector 1.



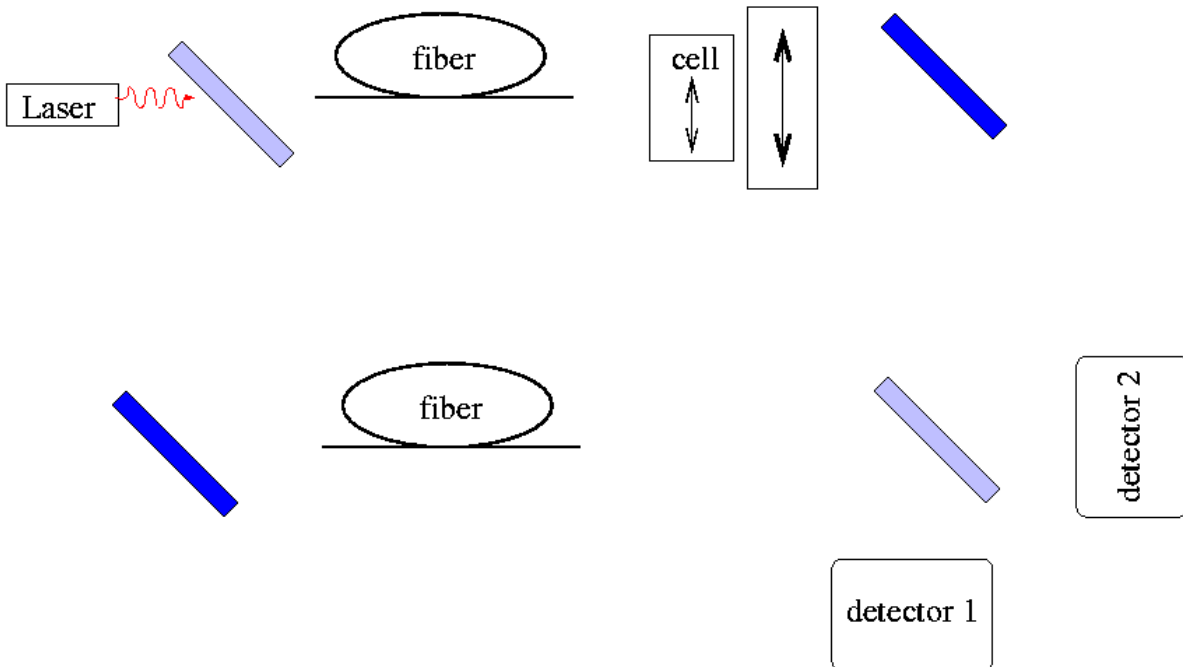
So, putting it all together, if light behaves like a photon, and we close the upper arm, we expect to see

	probability	Detector 1	Detector 2
blocked in upper arm	50%	0	0
lower arm, through	25%	0	1
lower arm, bounce	25%	1	0

Q: If we sent 200 photons into the device, what would we expect to read from the detectors?

**If light is a wave ...**

Now, suppose light acts like a wave instead. If we open the upper arm by setting the Pockels cell parallel to the fixed polarizer, light will go through both of the arms and interfere when it reaches the detectors:



The experimenters carefully arranged their apparatus so that the path along one arm was half a wavelength longer than along the other arm. If constructive interference

occurred at one detector, then destructive interference would occur at the other. The sum of the detected intensity would add up to 1.0, but it would be divided between the two in some way.

When Hellmuth and his colleagues ran the experiment, they discovered that small temperature variations in the fibers caused the exact path lengths to vary slowly, on timescales of a minute or two. That meant that the form of the interference drifted during their observations: Detector 1 would first have constructive interference, then it would gradually change to destructive, then back again. Their measurements looked something like this:

time (sec)	Detector 1	Detector 2
0	0.90	0.10
30	0.60	0.40
60	0.30	0.70
90	0.05	0.95
120	0.15	0.85

and so on.

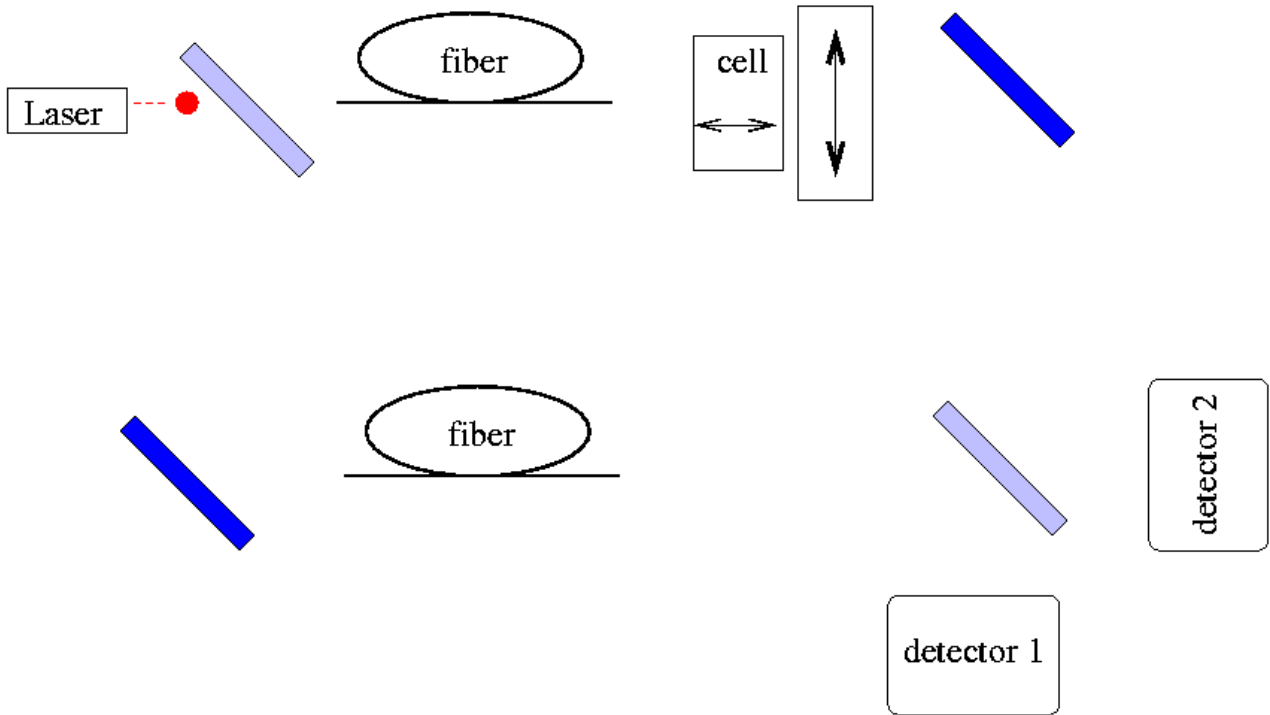
Q: If we sent 200 photons into the device, all during a 30-second period, what would we expect to read from the two detectors?

Q: Suppose we make many sets of measurements, over several minutes. Should these readings change with time?

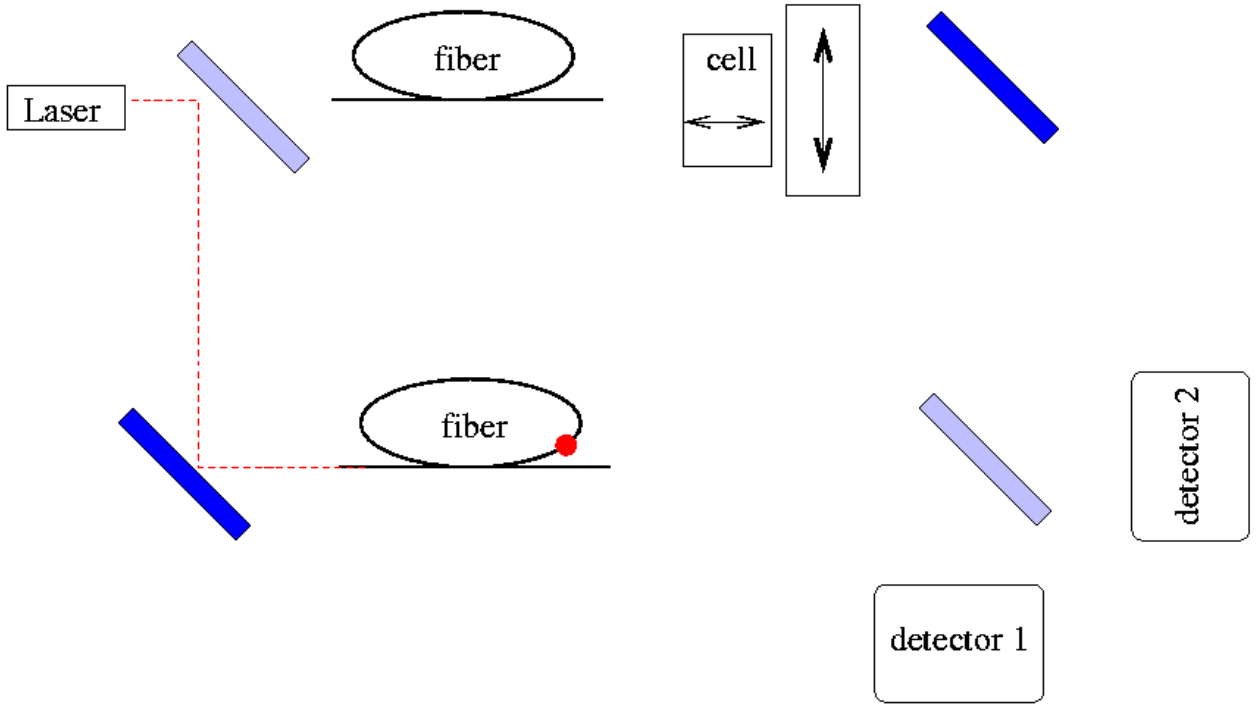
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### The delayed choice

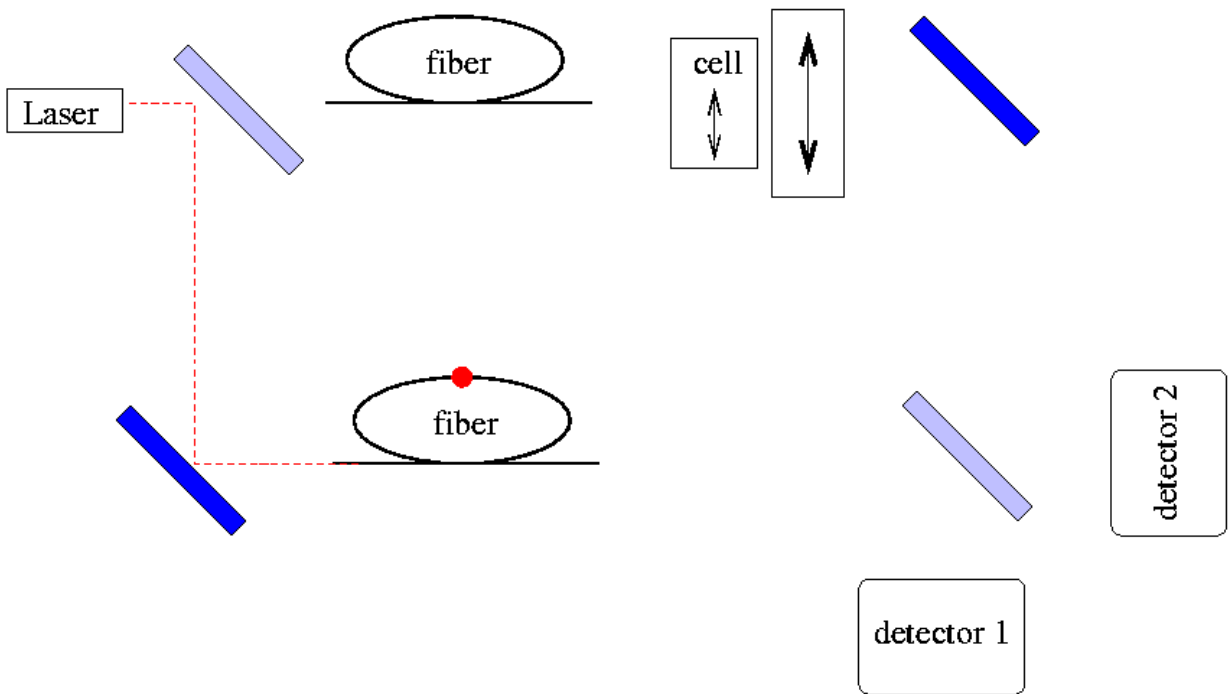
Now, here's where the **delayed choice** comes into play. Suppose that we start out with the Pockells cell set so that the upper arm is closed, and let a single photon into the device.



If the photon is "looking ahead", it will realize that in this situation, it can never reach the detectors along both legs; it can either go through the first beam splitter and be absorbed by the fixed polarizer, or bounce off the beam splitter and run through the lower leg. Suppose it takes the second route. We wait 15 ns, until the light has moved past the first beam splitter and into the optical fiber ...



and **NOW** we switch the Pockels cell so that it opens the upper leg:



What is the poor photon to do? It is "stuck" in the lower leg of the interferometer, and must continue so that it ends up in either detector -- but not both. There can be no interference in this case.

Q: If we sent 200 photons into the device, making the "delayed choice" each time, what would we expect to read from the two detectors?

Q: Suppose we make many sets of measurements, over several minutes. Should these readings change with time?

### **The crucial measurements**

There's clearly a difference between the measurements we ought to make if light is only a photon, or if light can be both a photon and wave at the same time. The scientists who ran the experiment arranged it to do the following:

1. Create pulses of light in the laser, then attenuate them so that the average number of photons in each pulse is only 0.2. In other words, (almost) always send either zero or one photon into the device.
2. For every odd-numbered pulse (1, 3, 5, 7, etc.), leave the Pockels cell set to "open", so that light can (and must) go through both arms of the interferometer and interfere with itself in the detectors.
3. For every even-numbered pulse (2, 4, 6, 8, etc.), wait until the photon moves into the fiber, and then switch the Pockels cell so that the upper arm is "closed." There should be no interference in the detectors.
4. Record the output of the detectors separately for the odd- and even-numbered pulses.
5. Run the experiment for an hour or so.

Let's look at their results:



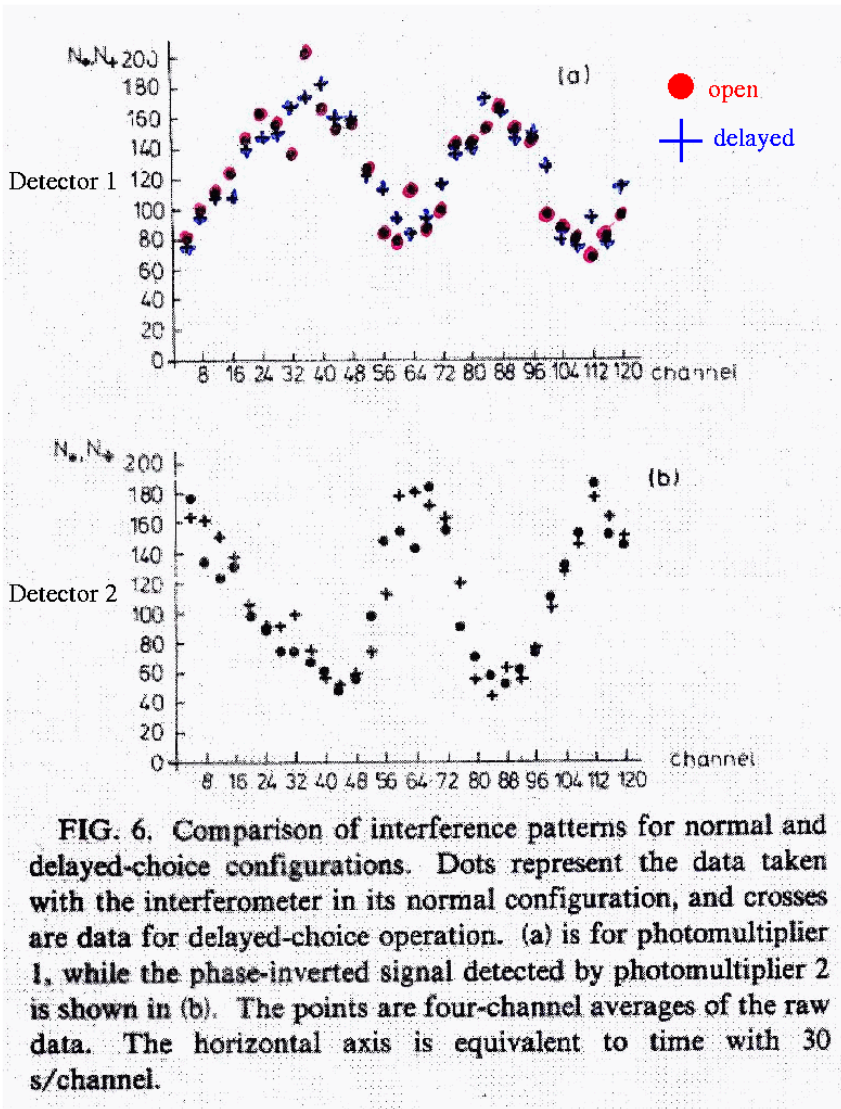


FIG. 6. Comparison of interference patterns for normal and delayed-choice configurations. Dots represent the data taken with the interferometer in its normal configuration, and crosses are data for delayed-choice operation. (a) is for photomultiplier 1, while the phase-inverted signal detected by photomultiplier 2 is shown in (b). The points are four-channel averages of the raw data. The horizontal axis is equivalent to time with 30 s/channel.

You can read a short essay on the puzzle of this duality by John Archibald Wheeler.

Source: <http://spiff.rit.edu/classes/phys314/lectures/dual4/dual4.html>