Quantum Erasers (Complementarity and Entanglement)

In our earlier discussions, we saw that closing the locality loophole involved switching between different analyzer orientations while the emitted photons were still in flight. The choice between the nature of the measurement was therefore delayed with respect to the transitions that originally created the photons.

Is it possible to make this a delayed choice between measuring devices of a more fundamental nature?

For example, in our discussion of the double-slit measurements, we found that if we allow a sufficient number of photons individually to pass through the slits, one at a time, an interference pattern will be built up. This observation suggests that the passage of each photon is governed by wave interference so that it has a greater probability of being detected (producing a spot on the screen) in the region of a bright fringe. It would seem that the photon literally passes through both slits and interferes with itself. As we noted earlier, the skeptical physicist who places a detector over one of the slits to show that the photon passes through one or the other does indeed prove their point - the photon is detected, or not detected, at one slit. But then the interference pattern can no longer be observed.

Advocates of local hidden variable theories could argue that the photon is somehow affected by the way we choose to set up our measuring device. It thus adopts a certain set of physical characteristics (owing to the existence of hidden variables) if the apparatus is set up to show particle-like behavior, and adopts a different set of characteristics if the apparatus is set up to show wave interference. However, if we design an apparatus that allows us to choose between these totally different kinds of measuring device, we could delay our choice until the photon was (according to the local hidden variable theory) "committed" to showing one type of behavior. We suppose that the photon cannot change its "mind" **after** it has passed through the slits, when it discovers which kind of measurement is being made.

Delayed Choice or Quantum Eraser Experiment

As we said, QM says systems can change behavior depending on measurements made on them or in response to a decision that has not yet been made. One part of an entangled pair can affect properties of its partner instantaneously, no matter where in the universe partner happens to be.

A so-called **quantum eraser** experiment has now been done...it dramatizes several aspects of quantum strangeness at once.

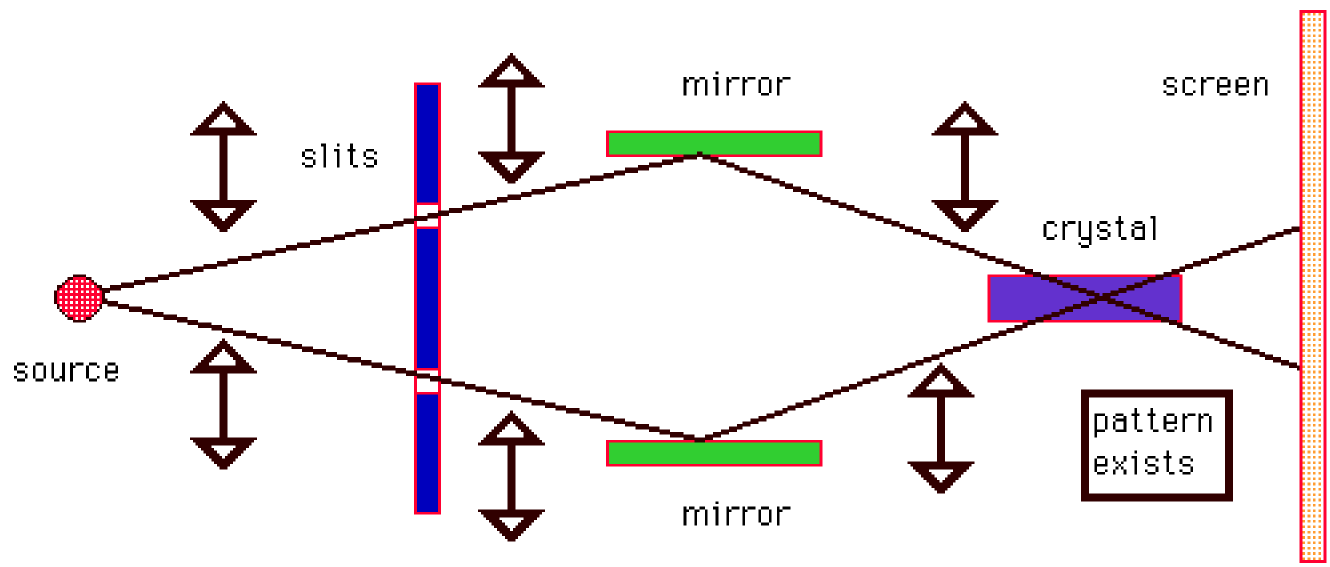
These experiments dramatically show the non-local effects, i.e., the ability of an experiment in one place to influence the outcome of another regardless of time or distance--but without transmitting any signals.

The idea behind a quantum eraser is to make paths(like those in a 2-slit system) distinguishable, which eliminates the interference effect, but then erase the "which-path" information just before the light reaches the screen where we actually observe the interference pattern.

QM predicts that the interference pattern should then reappear and it does.

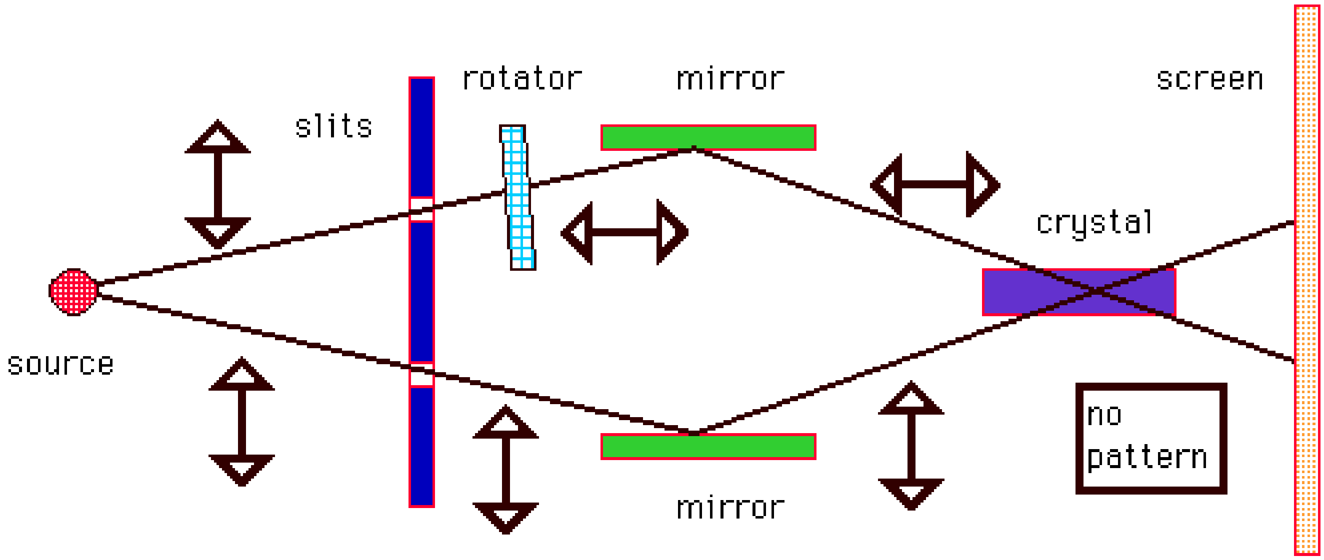
A quantum mystery of the following sort. A photon approaching slits will need to know whether or not there is an eraser further down the path(in its future), so that it can decide whether to pass through slits as a superposition of all possibilities (paths are indistinguishable) and produce an interference pattern later on the screen or that it should behave as a "particle" (paths are distinguishable) and produce no interference pattern **later** on the screen!!

An early eraser experiment can be visualized as a two-slit experiment as shown in the diagram below:

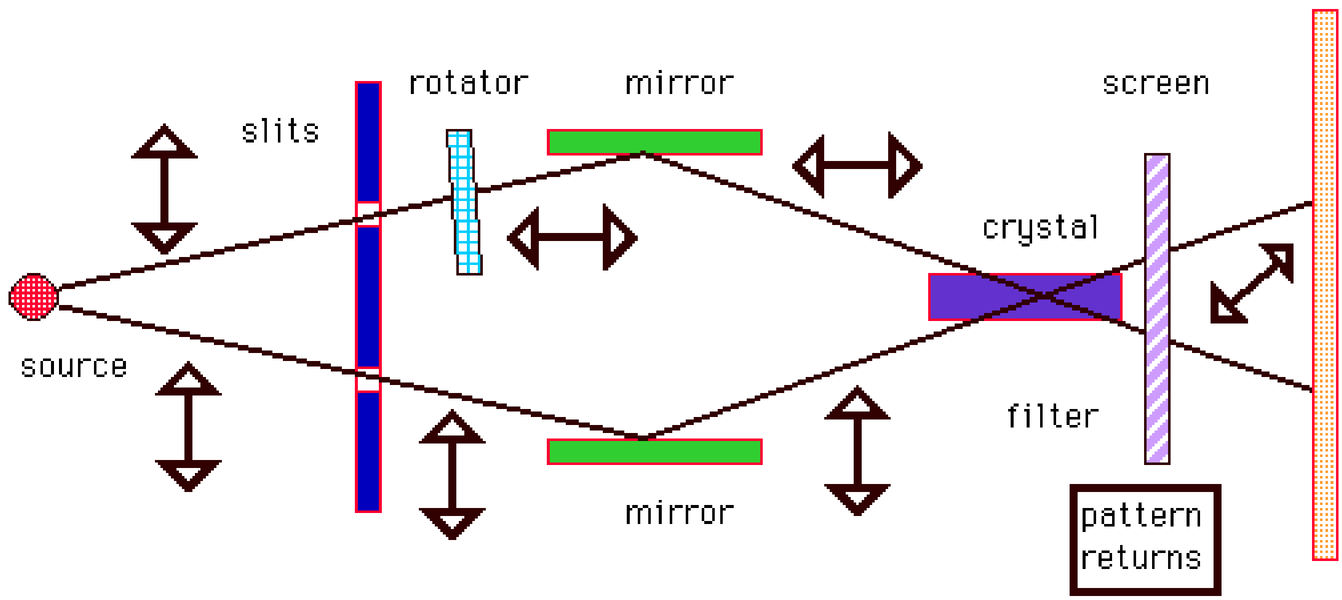


Photons passing through a double slit are all vertically polarized (indistinguishable paths). They can get to a recombination crystal by two paths as shown, which remakes a beam that produces an interference pattern on the screen, i.e., if paths are indistinguishable, then we have a superposition of all possible paths(2 paths in this case) and we get an interference pattern.

Now we insert a polarization rotator on one path only



and rotate the polarization of the photons to horizontal in that path. Since the paths now produce distinguishable photons, we get "particle like" behavior and the interference should disappear. It does! Now we add a **quantum eraser** after recombination (a polaroid at 45 degrees)

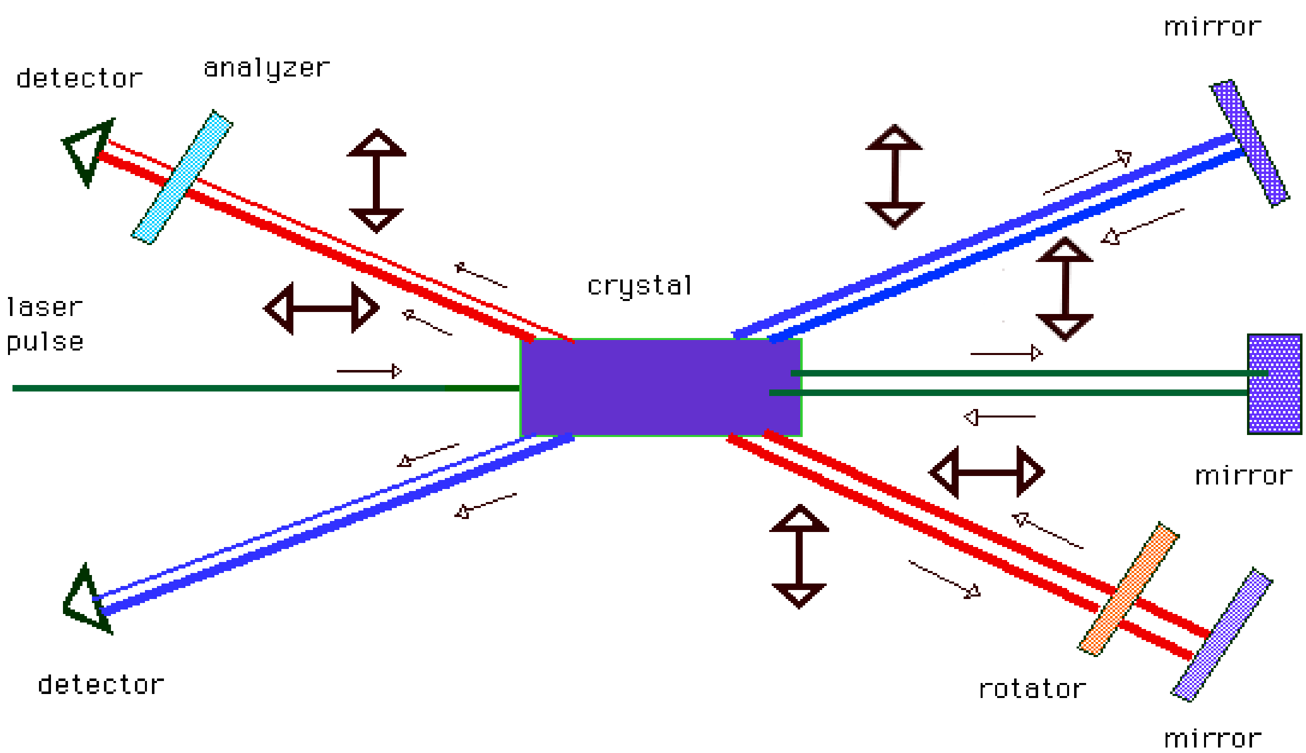


The polaroid filter produces equal numbers of photons with both vertical and horizontal polarization (with respect to new direction). Half of the new vertically polarized photons come from the horizontal polarized photons of the top path and half of the new vertically polarized photons come from the vertical polarized photons of the bottom path (similarly for the new horizontally polarized photons). It is impossible to tell whether a photon was vertically or horizontally polarized before the eraser. Thus, the two paths are once again indistinguishable. If interference pattern reappears, then a photon approaching the slits somehow needs to **know** whether or not there is an eraser down the line so it can decide whether to pass through the slits as a superposition(wave) and produce interference effects or as a mixture(particle) and produce no interference. The pattern reappears immediately confirming the quantum mechanical prediction. The filter erases the which-path information caused by the rotator. **A truly astounding result.**

What does this say about the classical idea that it is the two-slit system that is the "real" cause of the interference pattern?

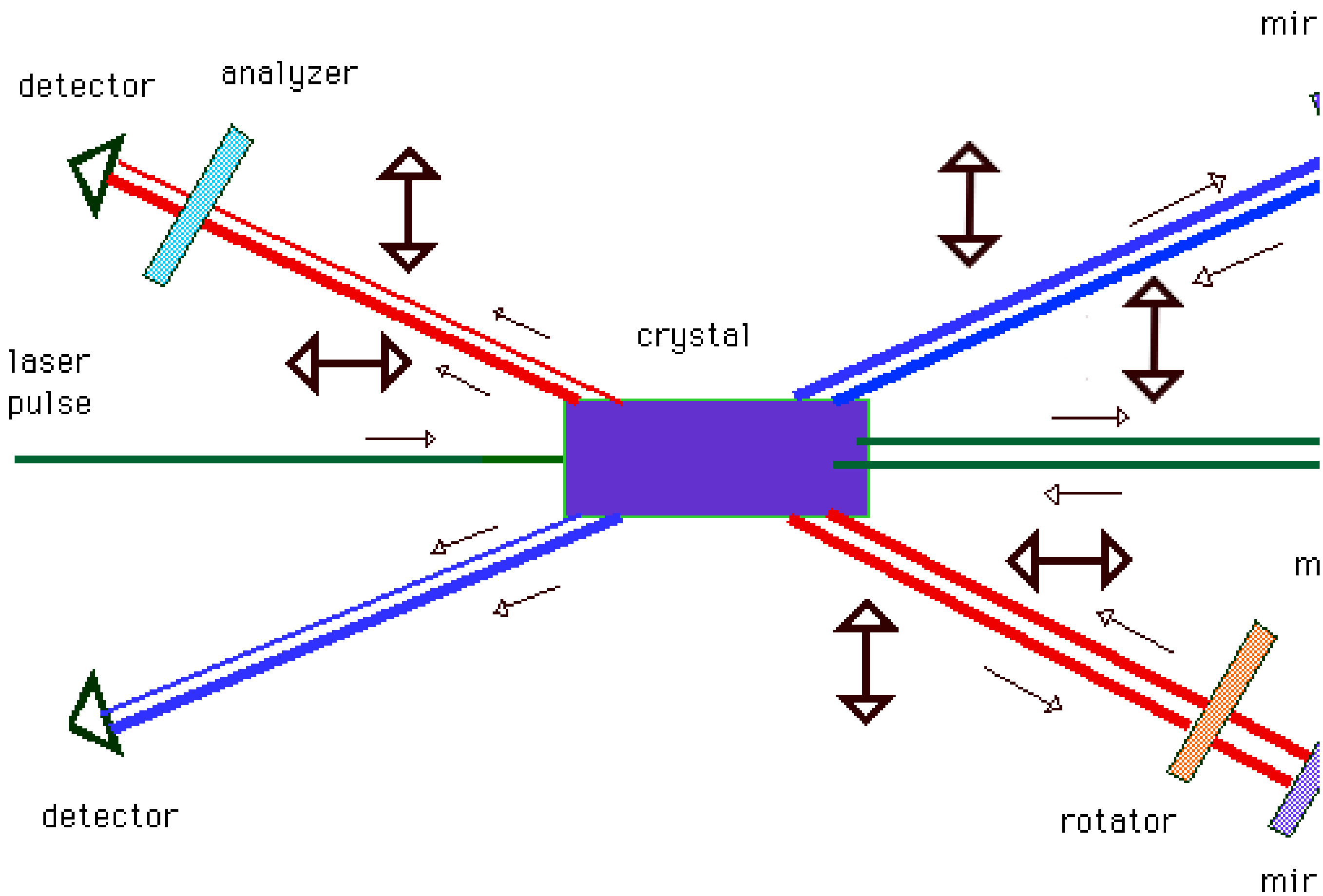
Worry : Experimenters, knowing the fundamental importance of these results, wanted to leave no possible source of controversy intact. In the above version of the experiment, there is a potential problem because the which-path information is carried by the same photons that interfere, making the experiment difficult to interpret.

A new version of experiment... Here which-path information is not carried by what one would naively call the **interfering** photon. Instead, it is carried by 2nd photon and along way it also demonstrates the striking non-local effects of QM. The experiment looks like:



High intensity laser photons are sent into parametric down-conversion non-linear crystal such as lithium iodate. The crystal converts some incoming photons(green) into pairs of identical photons with lower energy and vertical polarization moving at an angle to the original direction. The photons are produced as entangled partners. A measurement on one photon automatically tells us about the other with no direct measurement on the 2nd photon necessary.

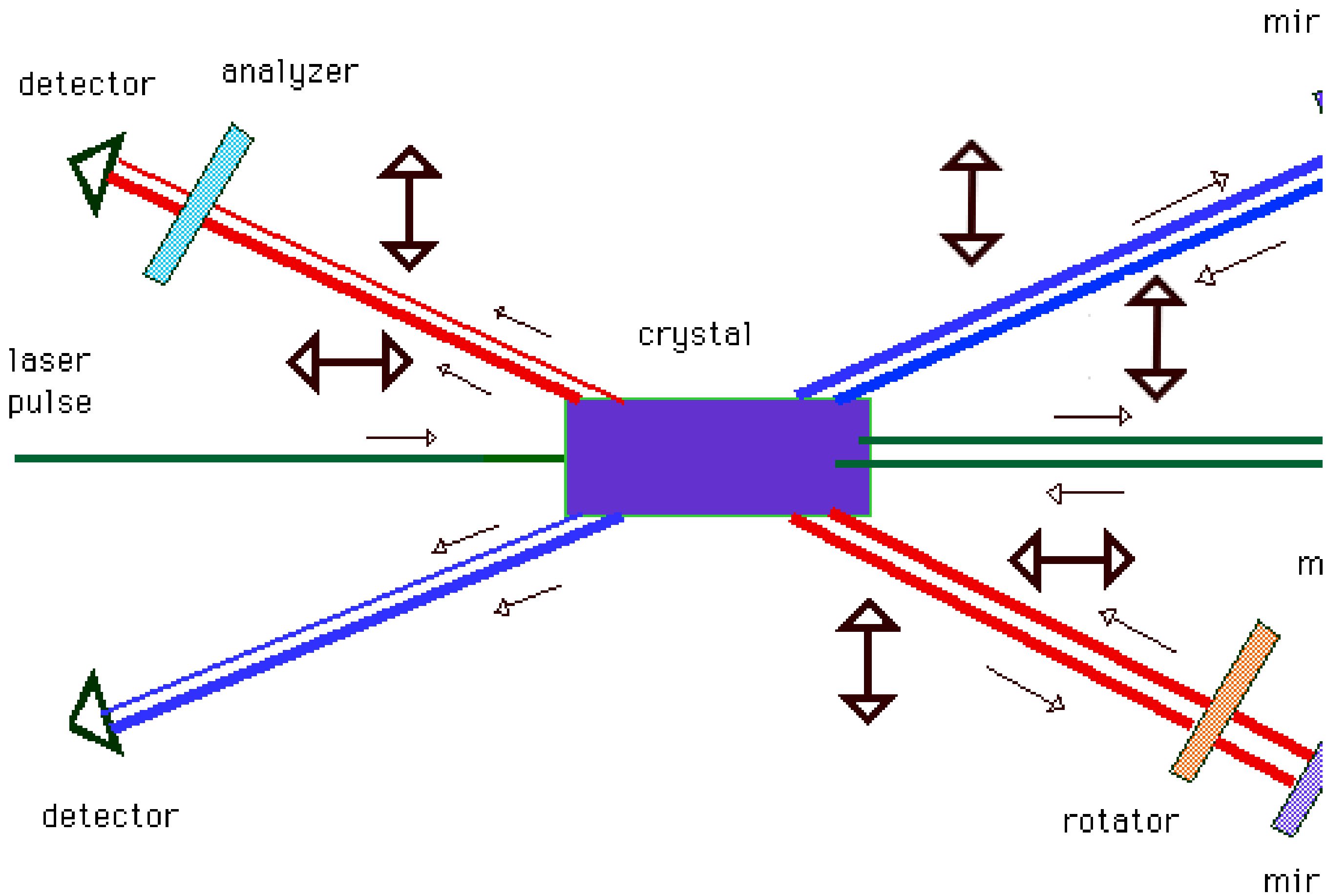
Twin beams exit crystal at an angle to the original path. These are the thick red and blue lines.



They are reflected back towards the crystal by mirrors and pass straight through it to detectors (the intensity is now too weak to cause down-conversion). These are the thick red and blue lines.

However, not all the laser light gets converted on 1st pass.

Some goes straight through the crystal to another mirror(green) and is reflected back into crystal(still high intensity) where the crystal creates more photon pairs which then follow same path as other beams to detectors. These are the thin red and blue lines.

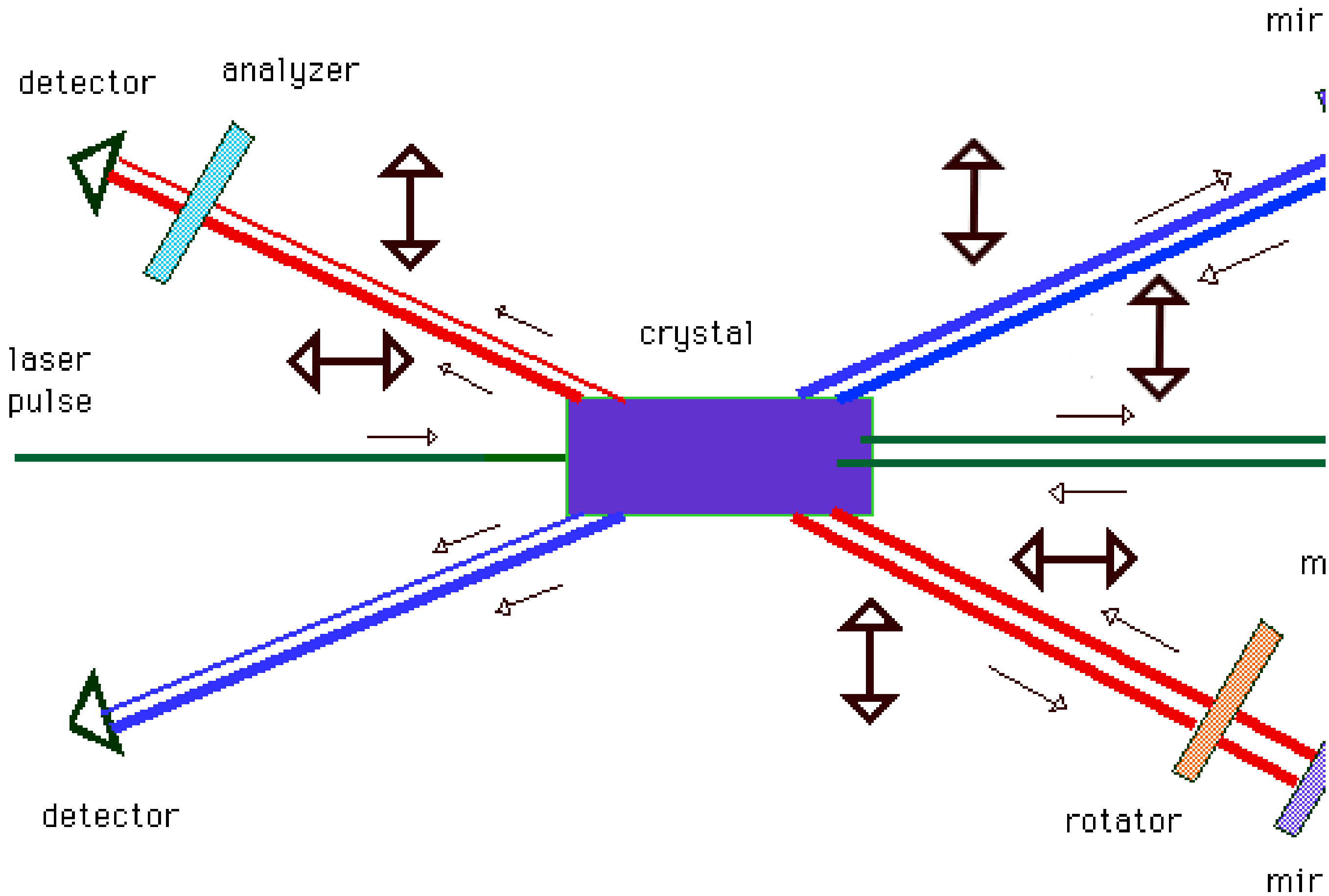


As a result, we have two different beams heading towards each detector each having follow different paths.

Each pair of beams corresponds to a separate double slit experiment

If there is no way to distinguish the photons created on first pass through crystal from those created on 2nd pass(and there is not), both detectors should have interference patterns and they do!!

We now make one returning beam in one leg distinguishable from other by inserting a polarization rotator into red path(as shown below) converting vertical to horizontal polarization in that leg.



The interference pattern in the top detector vanishes instantly as it should since the two (interfering) beams now have distinguishable paths.

Now, however, we also find that interference pattern disappears in left detector!!!!!!!

Why?

We have done nothing to disturb these beams so that the beams in the bottom detector still correspond to indistinguishable paths and photons!!!!

Remember, however, that the photons are created in entangled pairs, so when the red-path photons become labeled with which path info, the same info becomes available to blue-path photons, no matter where they are!!!

This is **non-locality** at work.

To erase the "which-path" info, we now add a 45° polaroid in red path, just in front of detector.

The interference pattern immediately reappears in top detector as it should (same as previous experiment).

It seemed however, that pattern did not reappear in bottom detector. One might imagine this is so because erasing red-path photon information does not erase any information from blue path

In addition, if it did reappear immediately, then we would be able to send signals faster than light with such an eraser.

However, as in EPR experiment we find, if we bring two data sets back together and compare them, the pattern had, in fact, been restored along both paths (need both data sets) to see correlations among the individual photons. Alternatively, one can do a coincidence measurement , which only looks at those photons counted in each detector simultaneously and one can see the interference pattern return directly, that is, the "which way" and interference effects are being recorded for **single** photons.

Thus, inserting or removing which-path information transforms the behavior of light throughout the entire system simultaneously demonstrating the amazing quantum eraser and the dramatic non-local behavior of QM.

This experiment makes it clear that there is a direct relationship between tests of complementarity and tests of quantum non-locality. Interference effects are the direct manifestation of non-local behavior. These effects can be "encoded" in the mathematical structure of quantum entanglement - in this case, entanglement of the states responsible for interference with the state used to detect "which way" information. These states cannot be disentangled without forcing the system to reveal one type of behavior or the other. They cannot be disentangled to reveal both types of behavior simultaneously.

Though still a subject for debate, a consensus is building that complementarity - and hence non-locality and entanglement - is the mechanism for the mutual exclusivity in the dual wave-particle nature of quantum objects, what Richard Feynman described as the "central mystery" at the heart of quantum mechanics.