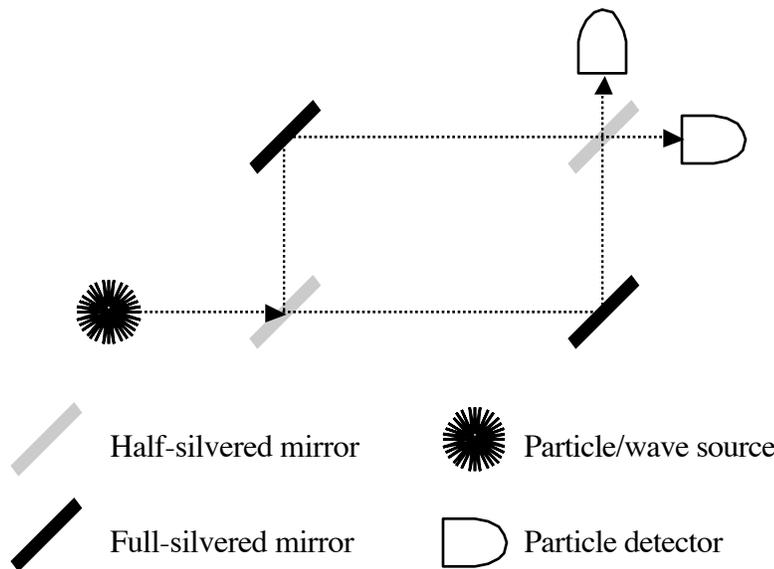


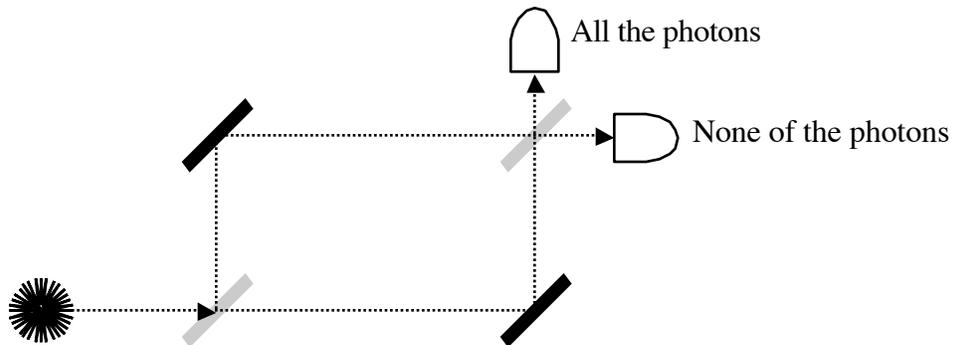
Quantum Interference Experiments

At the beginning of the class we looked at the two-slit experiment. The banded nature of the results of this experiment is naturally explained in terms of wave interference: the fact that two waves add to make a new wave. When the two-slit experiment is performed as particles and we still see banded patterns, we take this as evidence for the quantum wave.

There is a version of this experiment that involves a more complicated apparatus, but give a much more direct result. This version uses half-silvered mirrors to allow half the wave to pass through and half to be reflected. For particles, this means that half the particles pass through and half are reflected. The half-silvered mirrors are combined with normal mirrors and arranged in the following way:

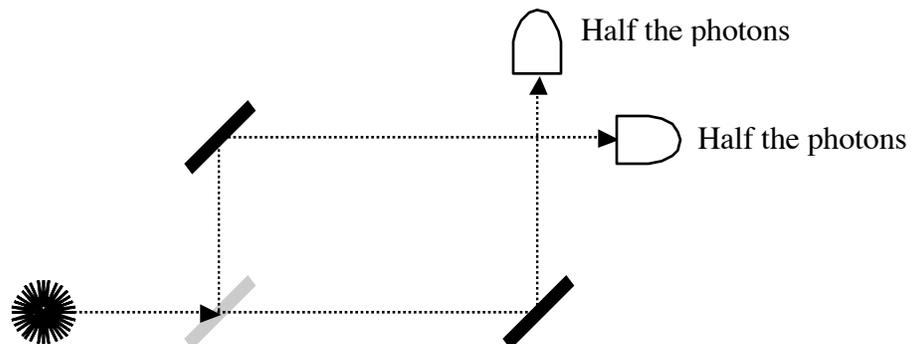


Let's say that we're working with light, so our particles are photons, though this experiment has been performed with protons and even neutrons. The idea is that the light from the source hits the first half-silvered mirror, which splits the light into two beams. The two beams are then bounced off of normal mirrors and reflected towards another half-silvered mirror. For the light beam that took the top path, this second half-silvered mirror causes half the top beam to be reflected up towards the upper particle detector, and half to go through to the side particle detector. Similarly, the beam that took the lower path will be split, but this time the reflected half will go to the side particle detector while the half that goes through will go to the top detector. The result will be that the light paths will be recombined by the second half-silvered mirror in away that when the beams from the two paths add up perfectly in one direction, in the other direction they will be exactly half a wavelength offset. When two sine waves that are offset by half a wavelength are added together they cancel out. Therefore if we arrange the mirrors so that, for example, the beam that goes into the top detector will see particles, then the side detector will see no particles at all. By moving the mirrors a little bit we can reverse the situation, so the side detector sees all the particles and the top detector sees no particles at all. This is easy to understand in terms of the interference of waves taking the two paths.



This is not so easy to understand in terms of particles taking the paths. Let's imagine we've arranged the mirrors so that the top detector sees all the particles. To make things really interesting, let's turn down the brightness of the source so that only one photon is emitted per second. Then there is no question that there is only a single photon in the apparatus at one time. What do we see? As we wait many seconds, so many photons have passed through the system, we will find that all the photons will be seen by the top detector. Does this mean that all the photons took the same path, say through the first half-silvered mirror, along the bottom and then up through the second half-silvered mirror? If we move the mirrors slightly we will find that now all the photons are seen by the side detector. Does this mean that now all the photons are reflected by one mirror and go through the other? It is hard to see why moving the mirrors would cause such a change in behavior.

There is another way to see what path the photons took: simply remove the second half-silvered mirror, so now the apparatus looks like this:



If we now rerun the experiment, what do we see? Half of the particles are seen by the top detector and half of the particles are seen by the side detector. This is true no matter how we move the mirrors. Of course this is exactly what we'd expect from both wave and particle descriptions (why?), assuming half the particles were reflected by the half-silvered mirror and half passed through.

So it seems that somehow when the second half-silvered mirror is there the different paths interfere with each other. As we said before, this is easy to understand from the wave point of view but is very difficult from the particle point of view. After all, a particle cannot take both paths, so how can the existence of the other path (that is, the one not taken by the particle) matter to what the particle does?

The Copenhagen interpretation would say that the presence or absence of the second half-silvered mirror changes the nature of the experiment. If the mirror is there, then we are observing the wave nature of light. If the mirror is missing then we are observing the particle nature of light, and half the time the photon took the top path and half the time the photon took the bottom path. (Of course the latter case can be understood in terms of waves also.) But this amounts to saying that the photon has wave properties when we do one kind of experiment and particle properties when we do another, but very similar kind of experiment.

We can make the conundrum even more stark by considering *delayed choice* experiments. What we do is wait until the photon has either reflected off of or passed through the first half-silvered mirror. Then we have a device that randomly either puts the second half-silvered mirror in place or removes it. This experiment has actually been performed. In other words we don't decide what kind of experiment it is until the photon has either taken the bottom or the top paths. Sure enough, when the second half-silvered mirror is in place all the photons are seen by only one of the detectors, and when the half-silvered mirror is removed half the photons are seen by one detector and half are seen by the other.

The moral of this story is that the quantum wave is absolutely necessary to understand such behavior. Trying to talk in terms of particles only cannot explain what we see without resorting to ideas like the particle knows what will happen in the future, namely whether or not the second half-silvered mirror will be placed or not.

Decoherence (Or Why There are No Half-alive Cats)

In this class we have been talking in terms of the conventional description of measurement in quantum mechanics, where you 1) predict the quantum wave by solving the Schroedinger equation, 2) decompose the predicted quantum wave into components appropriate to what you are measuring and 3) upon measurement you will see a result consistent with *one* of those components, with a probability determined by the amplitude of the component. So in Schroedinger's cat experiment, when you look the cat is either dead or alive with equal probability.

This story requires that on measurement the quantum wave *collapses* from a sum of components to only one of the components. There is no explanation in quantum mechanics of the nature of this collapse, and no explanation of why certain components are associated with certain physical properties of particles.

These last questions are addressed in what has come to be known as *coherence theory*. Coherence theory is really nothing but normal quantum mechanics done in a somewhat more realistic physical setting. In the past, quantum mechanics was used to describe highly idealized physical situations that were isolated from the rest of the world. Some of these idealized experiments are approximately doable. What decoherence tries to do is account for the fact that real experiments take place in interaction with the environment in the form of air molecules or light radiation.

It turns out that when you account for interaction with the environment the "mixtures" of various components of the quantum wave vanish very quickly. It turns out that all that is left (in the generic case of an environment made of randomly moving molecules or photons) is exactly the kind of bell-curved type wave that we have been using to describe particles with fairly but not completely accurately known positions and velocities. In other words the fact that position and velocity are somehow special for the quantum wave seems to be arising from the nature of interaction, as specified by the Schroedinger equation. Put another way,

decoherence shows that something like collapse happens as evolution by the Schroedinger equation.

Now what decoherence does not do is explain why we see the result we see. Decoherence simply says that we will see the cat either dead or alive. The probability interpretation But it is a major advance in understanding why we don't see a mixture of the two. The success of decoherence is one of the reasons that the many worlds interpretation is having something of a resurgence.

Though it is controversial, there are some who claim that decoherence combined with the many worlds interpretation can explain the probabilistic nature of quantum measurement.