QUANTUM THEORY

In short, quantum mechanics, special relativity, and realism cannot all be true.

Arthur Robinson, Science

In this chapter, we will take a look at how the RCM theory meshes with quantum mechanics. As the opening quote reveals, it is apparent that quantum mechanics, realism and the special theory of relativity cannot all be true. We have already shown that, in fact, the special theory of relativity is not true, which is good, because a world in which realism is not true is hard to imagine. Nonetheless, we have not accomplished anything if the RCM theory also fails to be compatible with quantum theory.

It is not the intent of this chapter to develop detailed or explicit models as to how photons interact with matter. Quantum mechanics as a discipline in itself has a great deal to say about this matter. Nor is there an attempt to explain exactly what happens at the point of photon-electron interaction when we observe "interference" on a screen. The goal of this chapter is simply to illustrate that RCM photons are compatible with quantum mechanics, and to further show that, utilizing RCM photons, we are able to explain observations which, utilizing relativistic photons, appear as paradoxes. We begin with a look at photon interference, which is the major catalyst for treating photons as waves in the first place. Next we will consider the double slit and the so-called delayed choice experiments in which it appears that a photon knows how we are going to observe it even before we, the experimenters, make such a determination. Finally, we will consider the nature of obtrusive versus unobtrusive observations in the example of Schrodinger's cat.

WAVE INTERFERENCE

Throughout this book, we have discussed light as having a frequency, which implies a wave nature to the individual "photons." We have also stated that light travels at all velocities from its source in the range zero to C, where C is at least as great as two times c. We will now consider some interesting implications of this arrangement.

Maxwell's equations clearly envisioned a wavelike property of light, propagating as a series of rising and falling electric and magnetic fields. In 1927, Einstein and Bohr began a series of debates concerning the nature of photon "waves" as they propagated through various single and double slit experiments. We must take the time to examine the strange nature of light as it goes through these setups in order to obtain a clear understanding for the nature of light developed in the previous chapters, and also to explain these eerie phenomena.

To begin with, if light is shown through a slit and onto a screen, the image on the screen is consistent with that of a wave (such as a water wave) passing through the slit and impinging on a wall. More importantly, if light is passed first through a single slit, and then through a double slit, as pictured in figure 10-1, the image on the screen develops an interference pattern of light and dark fringes, consistent with the way in which water waves passing through the same apparatus would reinforce each other where their crests coincide, and cancel each other where their crests and troughs coincide. This behavior continues even if the intensity of the light is reduced to the point where only one photon at a time passes through the apparatus. The end result over time of many photons passing through this system one at a time is a repeat of the interference pattern experienced when a continuous stream of photons is let through both slits, interfering with themselves on the other side. As strange as this seems, the story becomes more complex. If a detector is placed in each of the two slits which can monitor the passage of a photon , the photon appears to go through one slit or the other, not both, and the interference pattern disappears! It is as if the photon "knows" it is being observed, and therefore becomes a particle. Particles passing through a double slit experiment do not interfere with each other. To see this, imagine a pile of sand on a platform with two slits, some distance above another platform. Each grain will pass through one slit or the other, and you will be left with two piles of sand on the lower platform, one centered under each slit. From these two experiments, it appears that light behaves as both a particle and a wave, and chooses which one to become based on the way in which we choose to observe it. As will be shown later, the decision as to whether to observe the light as a particle or a wave can even be delayed until after the photon has passed through the double slit, and yet the photon will still "know" how we are going to observe it and behave accordingly, even before we make our decision.

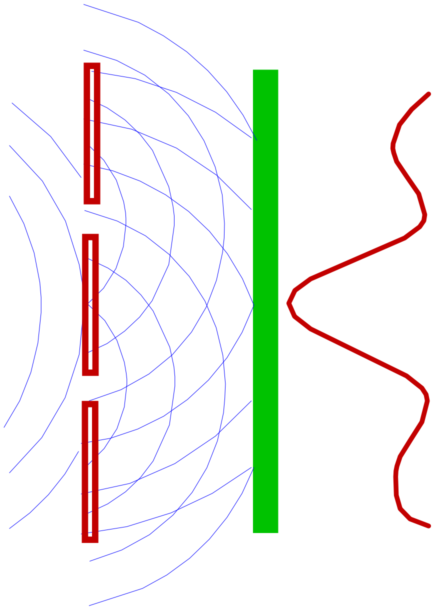

Figure 10-1 Light passing through a double slit will produce an interference pattern similar to the way in which water waves passing through such a setup would behave.

Quantum theorists state that we are stuck with an inability to describe the nature of light. All we have in the macroscopic world are waves and particles, not wave-particles. It is therefore, they say, not even possible for us to conceive as to what the true nature of light is as we have nothing to compare it with. We are left to simply view light as waves when that is appropriate, and as particles when that is appropriate, and be satisfied with that which we cannot know or understand. In the following paragraphs, we will take a brazen step forward, and see if we can't perhaps understand quite a bit more than the quantum theorists say we can.

When you visualize a wave, you probably imagine a beach, with a continuous stream of lazy waves rolling in. This wave, however, is made up of many millions of drops of water, each working together to make the wave train. One drop of water is not a wave. It may rise and fall in a periodic fashion, or may propagate toward the shore following the contour of the wave, but the wave itself is the collection of all drops which make up the wave train. For a given drop of water to be a wave, it would need to spread out in width and length, in order to produce more than one crest. In fact, a given drop of water can be considered only as one point on the wave. It cannot, at any one time, be both this crest and the one behind it or in front of it, nor can it be itself and the point next to it. Thus, a given photon in the usual sense of the word cannot be a complete wave which goes through two different slits and interferes with itself. To consider this further, consider a single pulse of a water wave in a tank with the double slit apparatus as in figure 10-2.

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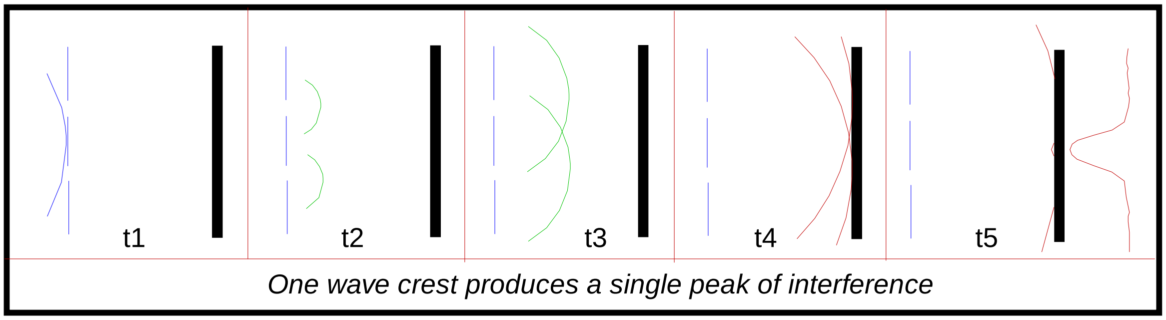


Figure 10-2 *A single wave pulse or crest cannot produce an interference pattern. Interference occurs when multiple crests coincide at the same point on a screen at the same time.*

Note that this single wave crest is made up of millions of drops of water, not one drop spread out across the entire crest. As the wave peak propagates through the double slit, we will see a single point at which the peaks of the wave coincide, midway between the two slits, on the far wall. Since there is not a continuos stream of wave pulses, the characteristic interference pattern (light and dark bands) will not arise. Interference will occur at one point only, that point where the path lengths from the single slit to the far wall are identical. The reason for this is that the propagation of this wave pulse occurs at a constant velocity along all paths. At any point where the path lengths are not identical, first the wave through one slit will hit the wall, followed by the wave from the other slit. No interference will occur. If we set the velocity of this wave front at c, we have the example of one relativistic photon wave passing through the slit. Thus, when one considers what is meant by treating photons as waves in the classical sense of the word, one is not viewing a wave train with each photon, but simply a single wave peak, as it were, propagating through the apparatus, and the interference pattern obtained in this manner should in no way resemble the interference pattern actually obtained. Actually, the usual picture of a photon invoked in quantum theory is as a "wave packet," which is spread out slightly in space. This is actually a probability envelope, rather than an actual extended wave. In this model, the amplitude of the wave at each point represents the probability of the photon being at a certain point, or of having a certain speed, with most of the probability centered around a speed of c. Invoking such a photon packet, however, only slightly alters the validity of the single photon argument presented above. It is worth noting that the wave-packets invoked in quantum theory produce photons with a probability of traveling faster than, as well as slower than, c, in conflict with Einstein's second postulate.

The only way to obtain interference at any point other than directly behind the center of the two slits from a single wave crest is for the wave to follow one path at a different velocity than the other path. In this case, interference would occur at different points, and would either be constructive or destructive depending on the ratio of the velocities and distances involved. In the classic example of a water wave, we get constructive interference when the crests or peaks of two or more waves coincide, and get partially destructive interference where other portions coincide. When the crests coincide, the waves are said to be in-phase. In destructive interference, the waves are out of phase to varying degrees. Two waves which are 180 degrees out of phase will cancel each other completely, and two waves which are 360 degrees out of phase will have come full circle, and appear to be in phase again. Without invoking specifically the picture of crests and troughs in photon waves, we can state that we will obtain constructive interference when two photon waves are in phase. Otherwise, we will get varying degrees of destructive interference.

Recall that, according to Einstein's second postulate, light travels at the constant velocity of c, from all reference frames, thus interference from a single photon as described above is not possible, since differing path lengths would require differing velocities of the wave components, such that both components strike the screen at the same place and at the same time. In fact, if one could accurately measure the time at which a photon struck a point on the detector screen, comparing it to the time the photon was initially emitted, one could determine which slit the photon went through without placing a detector at either slit, as we can see by looking at figure 10-3.

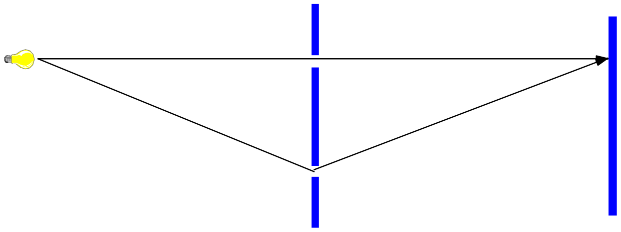


Figure 10-3 A single photon traveling at c would take longer to follow the lower path than to follow the upper path.

In figure 10-3, it is clear that the time from emission to hitting the screen traveling at a velocity of c will require that only one path could have been taken by the photon, either the shorter or the longer path, depending on the trip time. Thus, if we know the exact time of emission of the photon, and the exact time that the photon hits the screen, we can determine which path the photon took, even though we have no detectors placed specifically along either path. That it might be difficult to set up such an experiment is not important. According to quantum theorists, merely having the *capability* of determining which path the photon took requires it to behave as a particle, eliminating the interference pattern. Therefore, the above revelation, that the possibility exists to determine the path, even though it came *after* many thousands of double slit experiments have been performed all over the world, should eliminate any interference pattern observed, since the capability to multiply the trip time by c to obtain the path length and thus the path taken has always been available. Remember that the results of so-called "delayed choice" experiments indicate that the decision to determine the path can be made after the photon has chosen a path--presumably even years later.

Despite the above, the problems encountered in the quantum theory are not in treating a photon as a wave and a particle, but rather in the nature of the wave which is envisioned. Clearly a wave in the classical sense isn't in order.

Now consider the properties of a photon in the radiation continuum model of light. In this case, the photon is an extended particle or wave, which resembles a rubber band anchored at the source and being pulled forward with a velocity of C which may, in fact, be infinite. Along the length of this photon can be found a component traveling at any velocity between zero and C. The photon is associated with a given frequency which is the same at each point on the photon. Since the frequency is fixed, and the velocity changes, then the wavelength associated with the photon must also change along the entire length of the photon, being shorter at the slow velocity components, and longer at the faster components. This photon wave can be visualized as in figure 10-4. In the top half of this figure, we see an extended wave, whose wavelength gets increasingly longer with each faster velocity component. However, in this figure, the components traveling slightly faster or slightly slower than c appear to be 180 degrees out of phase with the component traveling at c. It makes more sense to assume that the "phase" of the wave is the same at all points, thus it is perhaps better to visualize the photon as in the bottom figure. In this figure, the photon is made up of a stream of ever increasing wavelengths, each of the correct length for the particular velocity component of interest, and each in phase with all the other components. In either case, it is important to realize that figure 10-4 is provided simply to give one a mental picture to use when thinking about photon waves, and is not intended, in either form, to be an actual picture of the way a photon wave actually exists. As Gunther Ludwig is quoted in *Space, Time And Mechanics*, "To claim that mathematical objects in a mathematical theory (as part of a physical theory) are also real objects is a deep misunderstanding of the nature of a physical theory." Nevertheless, the visual image provided gives us a tool for thinking about the behavior of "real" photons.

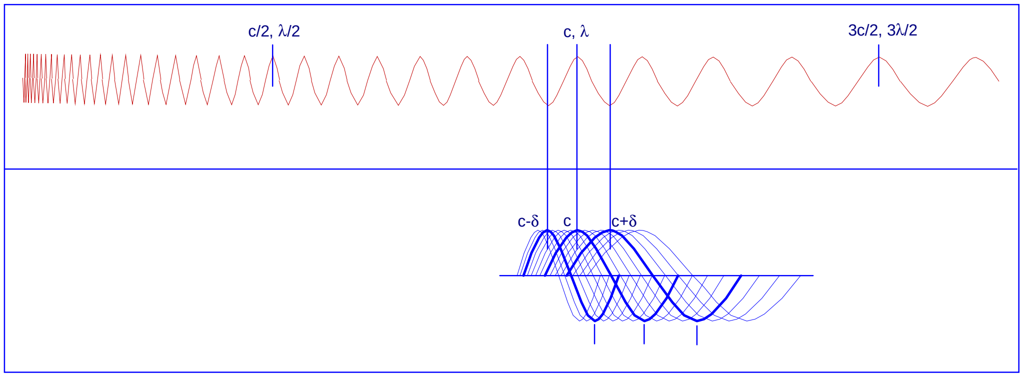
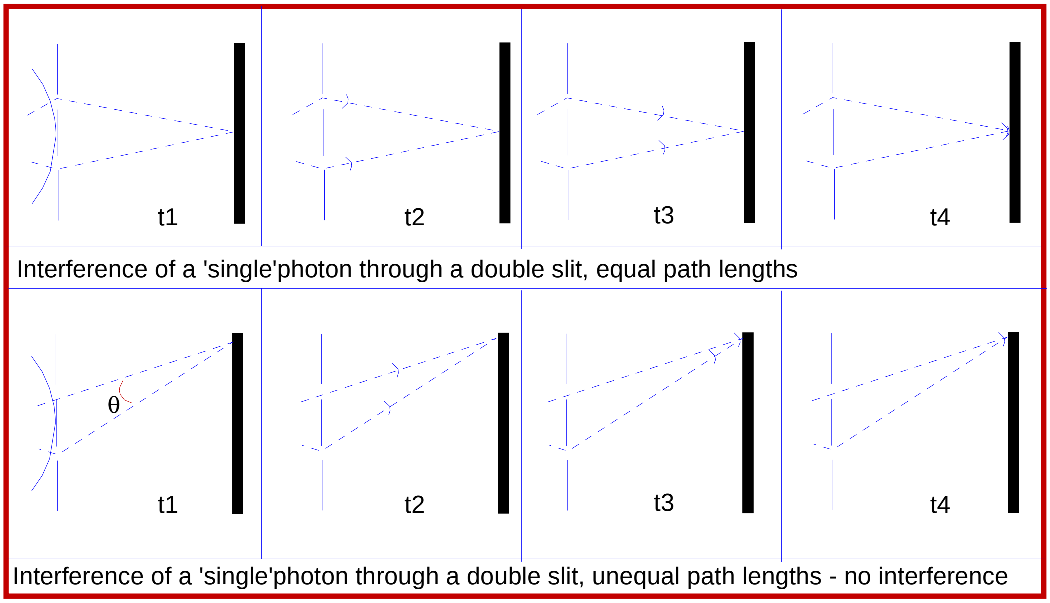


Figure 10-4 *A single photon wave has the same frequency at each point, given by the speed at that point divided by the wavelength at that point. Additionally, all components of a single photon wave are in phase.*

The wave depicted in figure 10-4 is a very unusual wave, and is not something that we would obtain by tossing a rock into a pond, but it is not, as the quantum theorists argue, something which cannot be imagined or visualized, as the figure clearly demonstrates. What is left now is to examine the properties of this photon wave and how it behaves in the particle-wave and delayed choice experiments.

Consider figure 10-5, which identifies two possible paths through the double slit apparatus. In the top figure, a single crest of a quantum photon wave impinges on the double slit, sending two new crests along paths which meet at the far wall. Since each generated relativistic crest is traveling at a velocity of c, and the two path lengths are equal, the two wave crests meet and constructively interfere with each other. In the bottom figure, however, we are interested in what happens at a point other than dead center between the two slits on the far wall. In this case, one generated wave crest has a much shorter distance to travel, and, thus, arrives at the wall before the second crest. The two paths of the photon do not interfere at this point either constructively or destructively, as they arrive at different times. The reason a water wave produces an interference pattern is that there is a continuous stream of wave crests, each one wave length behind the other. In the second case above, it is easy to see that another wave crest hitting the double slit just after the first would produce a crest which, traveling the shorter distance, would intercept the wall at the same time as the first crest from the lower slit. In the case of a continuous stream of constant velocity waves, as long as the path lengths are separated by specific multiples of wavelength, constructive interference occurs, otherwise, destructive interference occurs. However, quantum theory hinges on the ability of a single photon to interfere with itself, so this will not do.



Interference of a 'single'photon through a double slit, equal path lengths

Interference of a 'single'photon through a double slit, unequal path lengths - no interference

Figure 10-5 *A single wave crest cannot produce interference at a point other than midway between the two slits.*

Next let's consider a radiation continuum light wave. We have seen how a single wave front, traveling at a fixed velocity of c, such as is imagined in the relativistic theory of light, can produce an interference pattern only where various paths coincide in length. With an RCM photon, however, each photon wave front contains many different velocity components, all in phase. Thus we would expect that we should get interference at more than one point. Such is the case, and we will begin by considering the case of light traveling through a single slit.

SINGLE SLIT PHOTON INTERFERENCE

Imagine a source of light shining through a rather large slit in a wall, and continuing on to a screen some distance beyond. We must assume light of one color, or frequency, so that all photons have the same energy or frequency. As you might imagine, the point on the screen directly in line with the light source becomes brightly illuminated, while other parts of the screen remain basically dark. As obvious as this situation seems, it provides a very good starting point for our analysis of various experiments, so we will consider it in detail.

Frame A of figure 10-6 illustrates the case described above. Each of the lines in this figure shows one possible path that the photon wave could take to reach the point directly behind the slit on the screen. In fact, we can imagine the photon wave as fanning out from the source, and then converging at the screen. The question, of course, is why do these paths converge at this point rather than some other point, or why do they converge at all? The answer, as we shall see, is that this is the only point where all the paths constructively interfere. At all other points, the wave fronts cancel each other out almost completely.

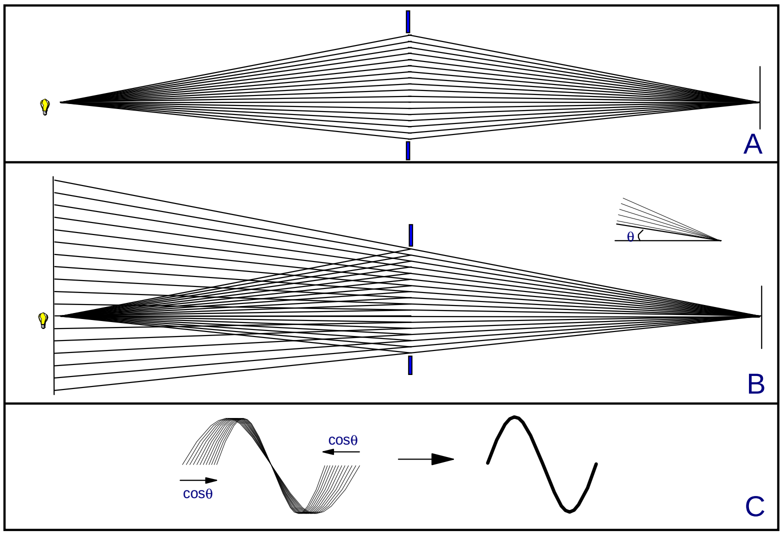


Figure 10-6 *Light appears directly behind a large slit in a wall because that is the point where all the in phase components of a photon wave converge.*

In frame B of figure 10-6, we have straightened out each path to the detector screen to show its equivalent straight-line length. One of the significant points about frame B is that each of the paths appear to start on a line drawn perpendicular to the actual straight line path from the source to the detector, or, more explicitly, from the detector through the center of the slit in the wall. The length of each of these paths is related to the fundamental straight-line path from the source to the screen by the angle that each path makes with this fundamental path. If we wish for each of these paths to reach the screen at the same time, then we must concern ourselves with faster velocity components on the longer paths. The velocity of these components is also related only to the angle formed with the fundamental path, and the relation is identical to that for path length. Now, each of these faster components will have an associated longer wavelength, as we saw in the previous section and earlier chapters. Thus, as all these paths converge at the screen, we would see a collection of wavelength components such as is pictured in the left hand side of frame C in figure 10-6.

Each of these converging components will have a different velocity, a different wavelength and a different angle of incidence. However, if we rotate each of these components through the angle they form with the fundamental path, some interesting things happen. Consider one component only, at some defined angle to the fundamental path. The velocity of this component is made up of two components related by the Pythagorean theorem. One of these components is c, and it lies along the fundamental path. This is why all the paths reach the screen at the same time. The other component is perpendicular to this path and depends only on the angle. The ratio of the c component to the actual velocity is known as the cosine of the angle formed. Likewise, the wavelength can be projected onto this fundamental line, also by multiplying by the cosine of the angle. This effect is the same as we experience in, say, rotating a pencil. As the pencil is held in front of us, we see its full length, but as it is rotated, it appears shorter and shorter, until we are viewing it head on and it appears to have no length. For each of the light paths in figure 10-6, the skewing of the velocity and the shortening of the wavelength are identical in magnitude, and both effects are related only to the cosine of the angle through which we rotate the wave.

Thus, after rotating or projecting one of the divergent paths onto the fundamental path, we have the equivalent of a wave front traveling at c, with the same wavelength as the component actually traveling at c, arriving at the same time as the "fundamental" component. This is true for all paths in frame B of figure 10-6. When we skew the wavelength of each incident component in frame C by the cosine of the angle involved, we are left with the situation in the right side of frame C. All the components appear to be the correct wavelength, all appear to be following the fundamental path at a speed of c, and all are in phase. Thus we get constructive interference and a bright spot on the screen.

But why don't we see a bright spot at other points on the screen? To understand this, consider frame A of figure 10-7. In this figure, we desire for the light to strike the screen at a lower point than in figure 10-6. If we extend each of the possible paths to their straight line equivalent, we get the top portion of the image in frame A. In this image, a line is drawn perpendicular to the fundamental path (a path which is arbitrarily chosen among all possible paths). If all path lengths began right on this line, we would have a situation similar to figure 10-6, where all components would converge in phase and constructively interfere. However, note that in figure 10-7 some paths are longer than the fundamental path while some or shorter. What this implies is that, even though we can find a velocity component for each path which causes it to reach the screen at the same time as every other path, the paths are no longer in phase. Each path is a fraction of a wavelength ahead or behind the path adjacent to it. Since the slit is wide, there are enough paths that the phase differences go from zero to 180 to 360 degrees several times. The result of this is shown in frame B. Instead of all the waves constructively interfering at the screen, even after projecting each component through the cosine of the angle made with the fundamental path, there are enough destructively interfering paths to cause the waves to ultimately all cancel each other out--thus almost no light is seen on the screen at this point.

There are, however, several ways to cause light to appear at this low point on the screen. One way is to make the slit very narrow. While it seems that this would just reduce the amount of light getting through the slit, which it does, it also causes the light to illuminate a much larger area of the screen. Consider figure 10-8. In this figure, the slit has been made so narrow as to allow only a few adjacent paths to get through. In looking at the top portion of this figure, we see that these path lengths are almost identical, except for tiny fractions of a wavelength. Thus, as frame B shows, each of these paths interferes constructively, and we find photon waves striking the screen at this point. The further down we try to find light on the screen, the narrower the slit has to be, as adjacent components become more out of phase as this angle increases. However, if we make the slit very narrow, and release only one photon at a time, we are just as likely to find the photon at a low point on the screen as we are at any other point on the screen, including directly behind the slit as in figure 10-6.

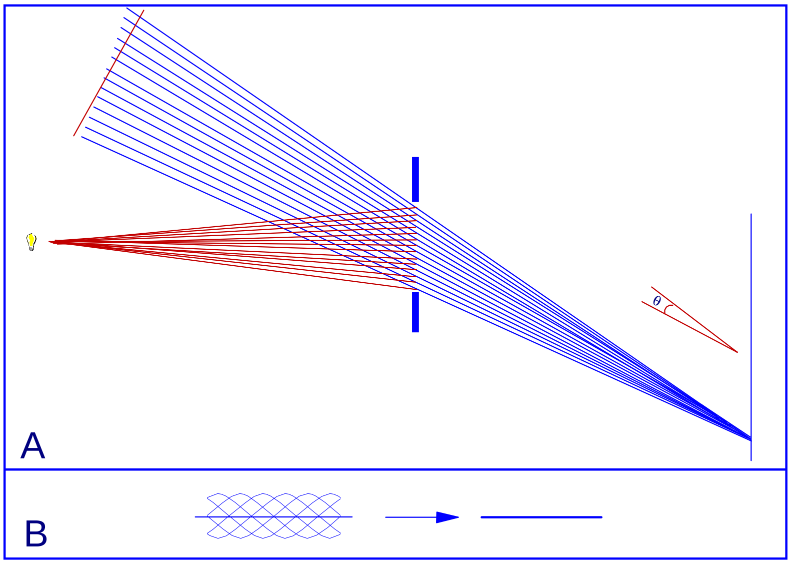


Figure 10-7 The components of a wave converging on a higher or lower point on the screen are out of phase and cancel each other.

Another way to cause light to appear at a lower point on the screen is to block out just those paths which cause destructive interference. This is accomplished as in figure 10-9. Looking at the top of this figure, we see that the paths which remain in tact are separated by a very specific distance. This distance is chosen such that the difference in effective path lengths for the components which get through the wall differ by integer multiples of the fundamental wavelength. In this way, each interfering component is out of phase by exactly 360 degrees, and thus appears as being in phase. All paths therefore constructively interfere, and we see a bright spot at this point on the screen.

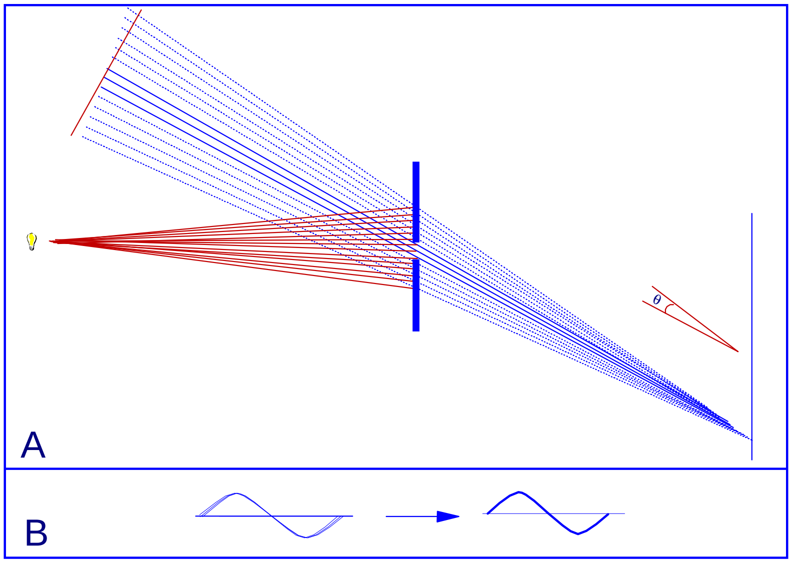


Figure 10-8 If the slit is narrow enough, light will appear with equal probability at any point on the screen.

If we move slightly above or below this point on the screen, the path lengths will no longer be separated by an integer multiple of the fundamental wavelength, the paths will destructively interfere, and we will not see light at that point, or we will see much less light, depending on the degree of interference. Also, if we change the frequency of the light, the points on the screen at which constructive interference will occur will change. If the path lengths at one point on the screen are separated by an integer number of wavelengths for one frequency, they will be separated by fractions of a wavelength for another frequency. For this reason, if we were to shine white light, which is made up of all colors or frequencies, through such an apparatus, we would see a rainbow effect on the screen. At the point where red light constructively interferes, for example, blue light would destructively interfere, and would not be seen. This is the effect one sees when viewing a compact disc at an angle. As the white light hits the disc, which has many closely spaced grooves, or slits, red light constructively interferes at one angle, while blue, yellow and green light all combine at different angles. This type of device is called a diffraction grating, and it can be used to cause a particular color or frequency of light to reflect off a surface at almost any angle one chooses.

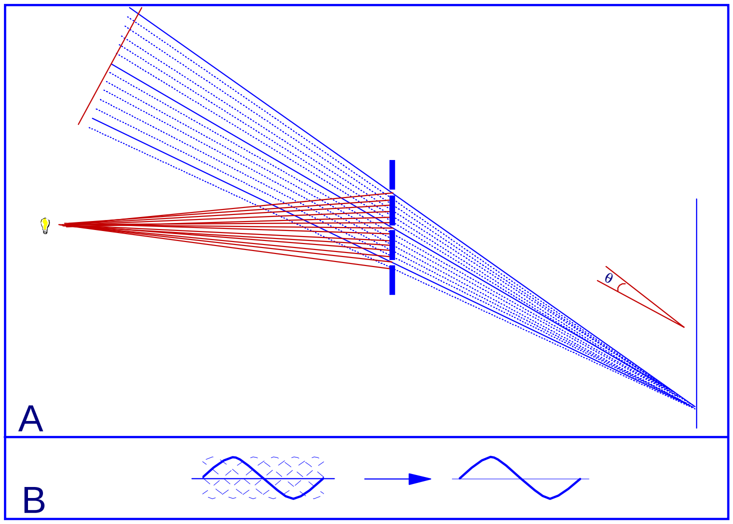


Figure 10-9 *If multiple slits are properly spaced, constructive interference will occur at clearly defined points on the screen, which are dependent on the distance from the source to the screen, the frequency of the light and the spacing of the slits.*

This last example provides our first taste of the double slit experiment--where we see wave interference as light passes through a wall with two closely spaced slits. But this is only half of this story. It is the other half of the story--what happens when we try to decide which slit a photon "particle" goes through--that gives apparently paradoxical behavior. However, before we study this experiment, we must first gain a little insight into the nature of photon detection and absorption.

PHOTON ABSORPTION AND DETECTION

How is it that we "detect" a photon? To begin with, it is important to note that we can detect a photon only by virtue of it's being absorbed by an electron. The change in state or energy of the electron can then be monitored or recorded, and we are therefore aware of the presence of a photon, whether the detector is an electronic photodetector, a phosphorous screen or our own eyes. Even though we design an experiment to detect photons with given properties, we will not detect every photon which matches those properties. No detectors are one hundred percent effective. There will always be some photons which betray our detectors and continue along their way, unperturbed by our experimental setup. Secondly, it is not completely feasible to provide an experiment whereby one photon at a time is released for study. This would require exciting a single electron in a single atom, and then allowing that electron to emit a single photon as it returns to its initial state. Hopefully this photon would have all the attributes we require for our experiment, notably a specific direction, but this would not likely be the case. To digress a little and get a feel for the numbers of photons involved in even a simple interaction, consider the following. We are in a room full of various objects and pictures hanging on the walls. We set up a camera at any point in the room, pointing in any arbitrary direction, then darken the room and open the camera shutter. Now a single pulse of a strobe light is released from the center of the room. When we develop the film, we see a picture of whatever the camera was pointed at. This requires that the single pulse of the strobe light emitted enough photons to illuminate every point in the room. As large as this number seems, it is only the beginning. Since we could set the camera up at *any* location, and point it at *any* object, then enough photons from that pulse must have hit *each point in the room* to cause each point to in turn emit enough photons to be seen from any other point in the room! In other words, if we were to draw a line from any point in the room (points being separated by as small a distance as you care to imagine) to a point on any object, then at least that many photons must have been emitted by that object during the experiment. This requires that that point on the object must have been bombarded by at least that many photons from the strobe burst. Similarly, every other *point* in the room would have been bombarded by as many photons as well. Each of these photons would have originated with the initial burst of the strobe light (not entirely true, since each re-emitted photon acts as a source of illumination, but the numbers are still mind bogglingly large). This is no small number of photons, even though the duration of the pulse is indeed very brief. Now imagine trying to devise an experiment whereby we release a single photon in a preferred direction. It is not an easy task. Regardless of this practical difficulty, we must next consider what happens at our detector or screen when a photon does strike it.

No matter what type of detector we use, the detector must interact with the photon in such a way as to cause an electron to absorb the photon's energy. A simple detector involves a screen which, when a photon of a given frequency strikes it, absorbs that photon and emits another, thus illuminating that point on the screen. If the screen is bombarded with enough photons of the correct frequency, the entire screen will become illuminated. Similarly, if a single band is bombarded, then that band will become illuminated, and the rest of the screen will remain blank. Now, we must consider what happens to a photon as it is absorbed by an electron. Recall that a photon is actually an extended wave (though not a wave as we are accustomed to thinking), anchored at its source and moving forward much as an elastic being stretched while anchored at one end. As the photon encounters the electron, given that it has the correct orientation and the correct frequency at the velocity component required by the electron, the entire photon will be absorbed. Thus, at the point of interaction, the entire photon wave is instantaneously absorbed, and collapses at that point, as illustrated in figure 10-10. Given that the entire photon can be instantly absorbed, and that theoretically, if it can avoid absorption long enough, its length may be many hundreds of light years, it becomes immediately obvious why the upper velocity limit of C approaches infinity. Since we have throughout this book dispensed with the idea that c represents some upper value of attainable velocities, this should pose no immediate problem. In fact, as we will show later, it allows the explanation of many "action at a distance" problems encountered within quantum physics. Secondly, the information about the photon pertaining to momentum, polarization, etc., is maintained to some degree in the absorbing interaction, and is passed on to the absorbing electron. When the electron then gives off another photon in place of the one absorbed, it often carries the same properties as the original photon, except that it begins anew, anchored at the source of emission and stretching forth at a maximum velocity of C.

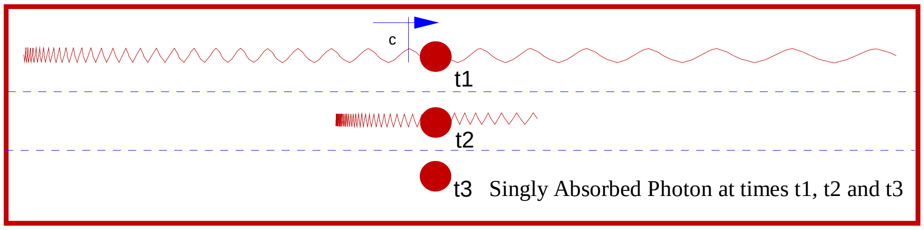


Figure 10-10 When a photon wave is absorbed, the entire wave collapses at that point.

To summarize, consider the following four properties of a "photon wave" which we have postulated in this section.

1) A photon has a characteristic frequency and is emitted from its source at all velocities from zero to C, resulting in a wave train represented by figure 10-4.

2) When a photon is absorbed, the entire wave collapses at that point, as in figure 10-10.

3) When a new photon is emitted, it generally carries the properties of the absorbed photon at the point of absorption.

4) The new photon is again a wave, this time anchored at the point of emission and traveling forth at all velocities from zero to C.

Armed with these ideas, we are now ready to attack the double slit experiment, and determine why photons appear to sometimes behave as waves and other times behave as particles.

The Double Slit Experiment

You remember the case of the experiment with the two holes? It's the same thing.

Richard P. Feynman

The reason I keep referring to the double slit experiment is that Richard Feynman, the author of Quantum Electrodynamics (QED), once said that, "Any other situation in quantum mechanics, it turns out, can always be explained by saying, 'You remember the case of the experiment with the two holes? It's the same thing.'"

We have been talking about how interference occurs at a point when different velocity components of a wave take different paths, but then meet at a point where, when superimposed on each other, the two components match in phase, thus causing constructive interference. Photon wave components passing by each other in space do not interfere. The components cause interference only at the point of absorption, if they happen to coincide at the same point and at the same time at which absorption occurs. But what is the nature of this interference? There are at least two possibilities, and perhaps many more.

- An electron absorbs what to it appears to be two photons, each with identical frequency, energy and orientation.

- An electron absorbs the properties of the two impinging components of the same photon, causing that electron to emit a new photon or photons with the same properties, which, in this case, would appear to be two new photons in place of the one self interfering photon absorbed.

Note that in each case, the end result is the appearance that two photons were available for absorption while in fact only one photon was emitted from the source. The important part of the above discussion is the following corollary to property two of the previous section:

> If a particle is in a position to absorb multiple components of the same photon as if it were two, then each of the photon's components will be absorbed, and the photon wave will collapse around the absorber as if it were two photons. The same can be extended to many components of a single photon, but the probability of exact coincidence of all parameters becomes increasingly remote with each added path.

We could also imagine a situation similar to the hydrogen atom in a gravitational well which we studied under the effects of gravitational potential on clocks. In this case, the gravitational potential energy caused the atom to be susceptible to a different frequency than it otherwise would be. Since a photon is generally represented as radiant energy, it is easy to see that constructively interfering convergent paths would provide the additional energy necessary to increase the likelihood of recording double photons. Likewise, destructively interfering paths would reduce the available energy for any detection to occur. Since a certain, well defined amount of energy is required for the detection to occur (given as the product of Planck's constant and the frequency), then converging negative and positive energy paths would reduce the total energy available below the detection threshold.

Fortunately for these discussions, the exact nature of the photon-electron interaction in the case of constructive interference need not be understood. What is important is that certain parameters relating to velocity, frequency and orientation be such as to allow absorption in the given environment. But in the case of interference, we are dealing with different velocity components. How is an electron able to react with a component traveling slightly in excess of or below the speed of c, when we have determined that all such interactions must appear to be at a velocity of c from the reference frame of the observer?

We have seen earlier how the nature of the hydrogen atom caused a clock based on the absorption characteristics of that atom to slow down when placed in motion relative to another such clock. That a given atom is susceptible to a range of values in these parameters is evidenced again by the hydrogen atom. Recall that the absorption frequency of this atom is *centered* around 1420 MHz. The reason for this is straight forward. Assume the atom is expecting a perpendicularly incident photon with a velocity of c and a frequency of 1420 MHz. Now a photon coming in slightly off the perpendicular at some angle, with an appropriately skewed velocity and frequency will be indistinguishable from a perpendicularly incident photon at the correct frequency and a velocity of c. From the hydrogen atom's reference frame, such a skewed photon would be absorbed exactly as if it were the photon the atom was looking for. From our reference frame, however, the frequency absorbed was slightly higher or lower than the ideal center frequency of 1420 MHz. There is a limit to how far askew the incident wave can be and still cause the required interaction, and, thus, the range of frequencies which can excite the atom drops off rapidly as we move to either side of 1420 MHz. The allowable range of angles or incident frequencies is obviously a function of the atomic structure, and as such is beyond the scope of the discussions here. Now back to the double slit experiment.

Figure 10-11 illustrates several ways in which two components of the same photon can move through the double slit apparatus. In frame A, each component is traveling at a velocity c, and strikes the screen at the same point. Clearly there is constructive interference here. The same is the case in frame B, except that this time, the angle is just the right amount to allow faster components and longer wavelengths to coincide in phase with the lower velocity components. For this to occur, the difference in path lengths as projected the cosine of their angle, as addressed earlier, must be in multiples of the fundamental wavelength of the incident light. Thus, to the screen upon which the two components are incident, the lower component may be projected exactly on to the upper component, as in figure 10-9. This component then appears to be an exact copy of the "wave front" coming from the upper slit, thus causing constructive interference.

In frame C, the two path lengths are not multiples of the fundamental wavelength, and, thus, the properties of the two components are not identical when they strike the screen. In this case, only one or the other or neither of the incidences will be recorded, and constructive interference will not occur. In fact, it appears that the destructive interference actually reduces the probability of either component being absorbed. Likewise in figure C, if the lower path were traced to intersect at the screen at the same point as the upper path, to produce an effect as in figures A and B, the two wave fronts would not project exactly on top of each other, they would be out of phase. The appropriate velocity components would not match up in phase, since the path lengths and angle are not such as to correlate to integer multiples of wavelength. To the atoms in the screen, depending on the level of interference, only one of these "photons" would have the proper characteristics to be absorbed. Or perhaps the negative energy well caused by the out of phase component would cause the available energy to be too low to allow for any detection. In either event, the end result is the same. We see bright bands where the path lengths are made up of integer multiples of wavelength, and darkness where such is not the case. At this point, even though we don't have a specific understanding of how an electron differentiates between a single photon, such as might pass through a one-slit apparatus, and constructive-destructive interference from two slits, we do see where the interference arises. There are many possible models of the photon-electron interaction which can explain why a single interaction is different from a combined interaction, but, as we have seen, such an understanding is not required for these analyses. With this in mind, we will defer such an understanding to future studies, and continue on with an analysis of quantum paradoxes.

While we have shown why an interference pattern emerges on the screen in the double-slit experiment, this is only half the problem. If the photon actually goes through both slits, or even only one, we would like to be able to know which is the case. When we perform the experiment with water waves, we can actually see the wave travel through both slits and interfere with itself. Such is not the case with light. In order to determine which path a photon takes, we must place photon "detectors" in the path of the photon. The easiest way to do this is to place the detectors in the slits themselves. In this manner, if a photon takes one path or the other, or even both, our photon detectors will click, and we can record the path taken. So far so good.

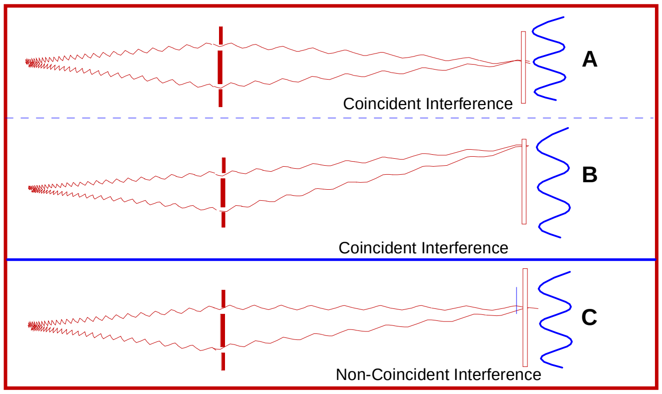


Figure 10-11 Another look at constructive and destructive interference in the double slit experiment.

When we actually place the detectors in the path of the photons, an amazing thing occurs--the interference pattern on the screen disappears! As soon as we set up the experiment in such a way as to "see" the photon waves traveling through the apparatus, the photons no longer behave as waves. They now behave as particles, going through one slit or the other, and collecting more or less directly behind the slits on the screen, much as in the pile of sand example used earlier. What happened to the interference pattern? The answer lies in the photon detectors themselves.

A photon detector is not a magical device. In order for it to detect a photon, it must interact with the photon in an obtrusive manner. In the simplest form, this involves absorbing the initial photon and emitting another in its place. Thus we know a photon has gone through our detector because we can read the increase in energy, and we then send another, basically identical, photon in its place. An actual photon detector, known as a photomultiplier, uses the incident photon to knock loose a single electron. This electron is then drawn toward a positively charged plate, gaining kinetic energy as it accelerates toward that plate. Thus this one electron knocks loose several electrons from that plate. These electrons are then accelerated toward another plate, where even more electrons are knocked loose. Eventually enough electrons are available to produce a sizable electric current which can be used to make a speaker click. The sound of this click can then inform an experimenter that a photon has been detected.

Now, imagine the photon wave components from a single photon as they are making their way through the double-slit apparatus. With no detectors present, the components make it through both slits and are able to interfere on the screen as described above. The photon is not absorbed until it hits the screen, and it is then that sometimes multiple components are absorbed as self interfering waves to varying degrees of destructive and constructive interference. Whether the photon interferes with itself or not, however, the entire photon is absorbed when it strikes the screen.

Suppose we now place a photon detector in each of the slits. Assuming a high degree of accuracy in our detectors, we will, of course, detect a photon at either one slit or the other, and never at both. When the photon interacts with the detector, the entire photon is absorbed. There is no longer a component of this photon traveling through the second slit which could later interfere at the screen. What happens instead is that an entirely new photon is emitted in place of the original. The behavior of this new photon has already been discussed and is described in figures 10-6 and 10-7. The photon will be detected on the screen almost directly behind the slit at which the original photon was detected, as in figure 10-6. Any other path contains too much destructive interference, as evidenced by figure 10-7. If we repeat this experiment with many thousands of photons, we find that about one-half are detected at one slit, and subsequently on the screen behind that slit, while the other half are detected at the second slit, and on the screen directly behind that slit. Suddenly we have results mimicking particle behavior, such as we saw with the two piles of sand.

Thus there is no paradox in this experiment at all. The original interference pattern disappears not due to any spooky knowledge the photon has about our experiment, but due to the fact that we change the experiment mid stream. Without the detectors, several components of a single photon wave can make it through both slits, and then converge on the screen with varying degrees of interference. While the photon might be detected, or absorbed, at any point on the screen, the probability, and thus frequency, of detection is much greater in the clearly defined areas where constructive interference occurs.

If we place detectors in the slits, we no longer have the same experiment. Once we place the detectors, on those occasions where they actually detect a photon, the original photon is absorbed and a new experiment begins--the emission of a photon from the detector. This photon does not travel through both, or either, of the slits in the wall. It is simply emitted from the detector towards the screen, and behaves accordingly. Likewise, the results of the experiment behave accordingly.

Note that I mentioned the importance of the detectors actually detecting a photon. Suppose we have detectors which are only fifty percent effective. We can repeat the experiment ten-thousand times, starting with the emission of a single photon each time. If we record separately the results of those cases where a photon is detected at one of the slits and those where no photons are detected, you can probably guess the results. In each of the cases where a photon was detected, the photons seem to collect on the screen directly behind the detectors. If we plot out the points on the screen where the undetected photons struck, however, we will be left with our familiar interference pattern. The same effect will occur if we put the inefficient detector in only one slit. For those instances in which a photon is detected, photons will appear to collect on the screen directly behind the slit. The photons which go undetected will exhibit an interference pattern.

Recall that in the study of clocks placed in motion, we saw how an obtrusive measurement altered the experiment. When Alice recalibrated a clock tossed into her reference frame, hers became the rest frame of that clock. This marked the end of the original experiment and the start of a new one. If Alice didn't tinker with the clock, but simply watched the elapsed time, the experiment remained unaffected. In the case of the photon experiments we have been considering, we must tinker with the photons in order to observe their behavior. This tinkering marks the end of the original experiment and the start of a new one, thus the results differ from the no-tinkering case. While Alice was able to observe the clock without altering it, there is no way for us to observe a photon without altering it--in this case, absorbing it completely. Only when we ignore this tinkering does an apparent paradox arise.

In order to get around this issue, different ideas have been proposed. One of these is the so-called delayed choice experiment. Such an experiment assumes we can allow the photon to interfere with itself first, and then observe which path was taken. A close look at any of these setups reveals that, although the equipment may be quite elaborate, we are again back to the situation just described--"you remember the case of experiment with the two holes? It's the same thing."

The Delayed Choice Experiment

There have been other variations on the double slit experiment which attempt to prove the existence of the wave-particle paradox. While several experiments have been performed, they all basically follow the one outlined here. The general idea is that if we let the photon go through the double slit first, and don't look at which path it took until after the fact, we should be able to get wave interference *and* particle behavior in the same test. One possible setup for such an experiment is shown in figure 10-12.

In figure 10-12, vertically polarized photons are emitted from a source one at a time. These photons then head toward a half silvered mirror. At this mirror, about half of the components of the photon wave pass straight through, while the other half are deflected at ninety degrees to their original path. Along these two separate paths, the waves next pass through a phase shifter, which will be discussed momentarily. From here the waves encounter and pass through a vertical polarizing filter. A series of mirrors places the waves on close, parallel paths, where they enter a modified prism. If wave components enter this prism in phase, they combine and continue on to photon detector D. If they combine out of phase, or if they come in from only one path, the photons are deflected to detector C. The entire apparatus is aligned carefully so as to ensure that all photons going through the system interfere in phase and are thus detected at D. When the apparatus is properly calibrated, detector D goes off every time, and detector C never goes off. Now on to the rest of the setup.

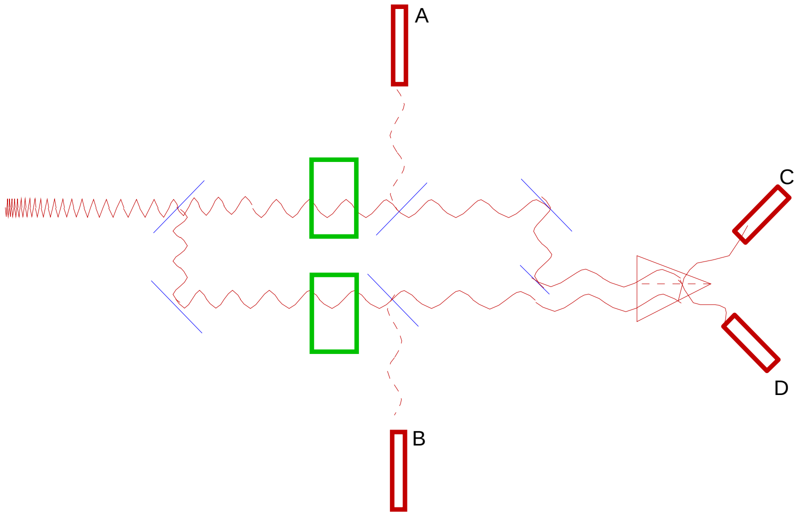


Figure 10-12 One possible setup for the so-called delayed-choice experiment.

The phase shifters in figure 10-12 can be electronically switched so as to change the polarization of the photons from vertical to horizontal. If the photons are horizontally polarized, they will be reflected off the vertical polarizing filters toward detectors A and B. With the phase shifters on, the photons are always detected at either A or B, and never at both A and B. It is argued that, in this case, the photon either goes straight through the first mirror or is reflected by it, but not both, thus the interference, which would be evidenced by a photon appearing at A and B, disappears. The rationale is that if we are allowed to know which path the photon took, it will always take one path or the other, but not both. Again, the interference appears only when we choose not to determine which path the photon took. Now for the delayed choice twist.

The phase shifters in figure 10-12 can be turned on and off very rapidly. In fact, they can be switched in less time than it takes light to travel from the first mirror to the shifters themselves. Thus, under the control of a random number generator, the phase shifters can be randomly turned on or off *after* the photon components have already passed the first mirror. Having passed this milestone, if the phase shifters are off, we get detections at D, indicating interference, and wave components taking both paths. If the phase shifters are on, we get detection at either A or B, indicating no interference, and, presumably, photon components taking one path or the other, but not both. The interesting thing, if this analysis is correct, is that the photon has to "know" whether to take one path or both paths, and do so, before the computer decides whether to turn the phase shifters on or off. The photon is able to predict how our computer will behave, and act on that "knowledge," even before the computer itself makes its decision. This "paradox" or predictive ability of photons has been verified many times, but, as we shall soon see, there is actually nothing confusing about the situation at all.

From the previous sections we saw why we get the interference at the prism, and thus detections at D, when the phase shifters are off. Now, imagine that the phase shifters are on, or that they will soon be turned on. As the experiment begins, as always, half of the photon components travel through the first mirror, while half are deflected. As these components near the phase shifters, they are turned on, and the components are deflected simultaneously toward detectors A and B. Now, as these components approach the detectors, either the component heading toward A, or the component heading toward B will actually be detected first. By detection, of course, we mean the photon will be absorbed. As we know, the entire photon will be instantaneously absorbed, thus there will be no component left to trigger the other detector.

At this point we must reiterate the fact that the photon detectors are not very effective. Most photons will not be detected at all. The fact that we have two detectors increases our likelihood of detecting a photon though. In fact, it doubles it. The ineffectivity of our detectors is predominantly responsible for the fact that when we do detect a photon, we detect about one-half at A and one-half at B. Otherwise, if the detectors were one-hundred percent effective, and the path length to A was slightly shorter than the path length to B, we would see almost all detections at A, since the components traveling that path would arrive first. However, if the detectors registered, say, ten percent of all photons, then the number missed by A and thus available for detection by B would be almost as great as those approaching A in the first place, and we would expect the detectors to go off almost equally. If an attempt is made to keep the distances to A and B as equal as possible, then even highly effective detectors would go off almost equally, since a photon traveling the two paths would have an equal chance of reaching A or B first.

Thus, there is no paradox, or predictive nature to the photon. The entire problem rests in the way in which we choose to interpret the results we obtain. Clearly, from the above, if we are very careful to consider the actual details of our apparatus, and the behavior of the photon within that apparatus, all paradoxes disappear. There is in fact no delayed-choice involved at all. The phase shifters are switched before the photon components reach them, and these components are then either reflected off the polarizing filters, or are passed through them, depending on the status of the phase shifter at the time the components go through them. All choices are made in advance, and all responses of the photon components are completely consistent with the status of the equipment at the time.

Schrodinger's Cat

Objective reality does not *have any place in our fundamental description of the universe, but action at a distance, or acausality, does have such a place.*

John Gribbins, *In Search Of Schrodinger's Cat*

Schrodinger's cat is, thankfully, a mythical cat, initially proposed to provide an example illustrating how ridiculous some of the ideas of quantum mechanics were. The hypothesized test goes something like this. A cat is placed in a box with a radioactive source, a vial of poison gas, a Geiger counter, and a hammer triggered by the Geiger counter. If the Geiger counter detects a gamma ray emitted from the radioactive source, it will cause the hammer to fall and break the vial, thus killing the cat. The parameters are set up such that, for the duration of the test, there is a fifty-fifty chance that the Geiger counter will trigger and that the cat will be killed.

Now, the experiment is performed, but the experimenters have yet to open the box and determine the status of the cat. Quantum theory tells us that, until the cat is observed, it is neither dead nor alive, but is instead in a superposition of states--a dead-alive cat as it were. The idea is that no observable characteristics actually exist until they are observed, presumably by a conscious observer. Debate still lingers as to whether the cat's own consciousness is sufficient, and the experiment has been proposed in other ways, such as using an ant or a human.

The fallacy in Schrodinger's cat arises in the same manner as we saw when considering Alice's effect on the clock thrown to her by Bob. It is not simply the act of observing the clock which causes the change in reference frame or state of the clock, but the fact that she made an obtrusive measurement. In the case of Schrodinger's cat, the nature of we, the laboratory observers, does not enter into the picture at all. Nor does the nature of the cat. The obtrusive measurement in this case is made by the Geiger counter, which absorbs the gamma ray, thus causing the release of the poisoned gas and killing the cat. The event, if it occurs, occurs whether are not we are there to observe it. The problem with the quantum theorists, as we saw earlier, is that *all* of their observations are obtrusive, thus they assume that they, the conscious observers, cause a change in the state of nature, and that, without their intervention, nature itself has no objective reality. Since the double-slit and delayed choice experiments seem to imply that photons and elementary particles choose to behave based on the way in which we view them, the conclusion is that they have no objective reality until we make our measurements.

We have seen that the apparent paradoxes in these experiments are do to the fact that we must completely absorb a photon to observe it--thus we begin a new experiment with each measurement. We have also seen that the detectors we use are sufficient to due the detecting, or observing, and thus change the experiment whether or not we actually watch the outcome. Such is the case with Schrodinger's cat. If the radioactive source emits a particle, and if that particle reaches the Geiger counter, then the cat is dead. Otherwise, the cat is alive. While the probabilities still exist, the Geiger counter itself is sufficient for determining the actual results of those probabilities. The entire road to this strange interpretation of reality--the road which led to Schrodinger's cat--can be traced directly to Einstein's second postulate.

Consider what is called the local realistic view of the universe. This view is based on three assumptions, or postulates:

V There are real objects that exist regardless of whether we observe them
V No influence can travel faster than light (a result of Einstein's second postulate)
V It is legitimate to draw general conclusions from consistent experiments

Quantum physics has demonstrated again and again that the local realistic view of the world is false. Thus, at least one of the above postulates must be false. We have shown throughout this book that it is the second postulate above, drawn from Einstein's own second postulate, that is wrong. By eliminating this postulate, we have a local realistic view which is at once consistent with quantum mechanics. In other words, there is no room for the constraints imposed by Einstein's second postulate and special relativity in either a local realistic view of the universe or in the world of quantum physics. Why pick on the second postulate, and not one of the other points? Most physicists today tend to leave the second postulate in place and attack the first. There aren't many attacks on the third, as this would leave those same physicists without a job. This argument, that objects or events have no objective reality until we observe them, is, in fact, the result of the so-called Copenhagen interpretation of quantum theory. Unfortunately, it is the act of keeping the second postulate in place that results in the seemingly bizarre behavior of photons in double-slit and delayed choice experiments, and leads to John Gribbins' statement at the start of this section. As we have seen already in this chapter, if we relax the second postulate, the eerieness of these experiments vanishes. There is, of course, another example of why the second postulate should be abandoned, and this was demonstrated in an actual test of a thought experiment known as the EPR paradox.

The EPR Paradox

The key to understanding the "EPR paradox" requires a brief statement of the Heisenberg uncertainty principle. This principle states that certain quantities or properties of an object come in complementary pairs, and that it is impossible to determine a precise value for each of the two properties exactly. For example, if we know exactly the position of a particle, then there is, inherent in the physics, a certain uncertainty in that particle's momentum. This is not a limit to our ability to measure these quantities, but is a fundamental uncertainty in the particles themselves.

We can create pairs of correlated particles, which means if we know the momentum of one, we can precisely deduce the momentum of the other, or, if we know the position of one, we can precisely derive the position of the other. Since the Heisenberg uncertainty principle disallows us from knowing both properties of one particle precisely, the paradox arises.

Albert Einstein, Boris Podolsky and Nathan Rosen proposed such a test in what came to be known as the EPR paradox. If we measure the momentum of one of these particles, then the position of the second particle must become ambiguous. This property must hold even if the particles have separated a great distance. Thus, if we decide to measure the momentum of one particle, the second particle must instantly know to have an ambiguous position. Likewise, if we measure the position of the first particle, the second must instantly know to have an ambiguous momentum. The problem, of course, is that these particles must somehow know how to behave instantaneously, implying information transfer in excess of the speed of c. Obviously Einstein could not accept such a proposition.

Actual tests of this "paradox" have been carried out. Several times using pairs of correlated photons, and, most notably by Alain Aspect, using correlated electrons. The results clearly demonstrate that the second photon or particle does know what we are doing to the first. This experiment demonstrates a confirmation of what Newton was initially uncomfortable with in his own theories--action at a distance is real. In other words, there appears to be no doubt that some type of information is shared instantaneously by these widely separated pairs, in direct contradiction to the second postulate.

In order to recover from these results, people have proposed that there is no real problem here, because we cannot use this property to build a radio or to send any useful information from one human to another. However, this is not what Einstein said. His postulate implied that *no* information could be transmitted faster than the speed of c. The Minkowski space-time diagrams, designed to illustrate Einstein's theory graphically, show areas which require a signal traveling faster than c to be reached labeled as "absolute elsewhere." This absolute elsewhere implies that nothing which occurs in that area can have *any* impact of any kind on the other areas of the diagram, and vice-versa. The Aspect experiments and others prove this contention false.

Recently, similar tests have been carried out to show that a macroscopic quantum device responds instantaneously across its entire length to a disturbance at one end. The far end responds faster than could be possible if information about the disturbance had to travel at a speed of c. Based on the results of this test, a larger device has been proposed which can actually be used to transmit information along the length of the device at a speed in excess of c (in fact, apparently at infinite speed). Though the device would be too small to be of practical use, it is obvious that it can be used to send useful information from one human to another, in excess of Einstein's information speed limit.

We can return to John Gribbins' statement at the beginning of the previous section, and conclude that he is wrong on two of three counts. First, as Gribbins said, action at a distance is real, and thus, the modified second postulate of RCM theory is supported. However, objective reality does have a place in a fundamental description of the universe, and acausality does not. Action at a distance is synonymous with acausality only if we accept the relativistic second postulate, otherwise they are unrelated concepts. Action at a distance becomes the instantaneous effect of a remote cause. Clearly, the second postulate, upon which the entirety of the special and general theories of relativity is based, is wrong.

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