2.6 Single photons acting as waves - the wave/particle duality

Even though photoelectric effect and Compton effect were instrumental in general acceptance of the particle picture of light, a direct observation of individual photons have only recently been made. There are a variety of ways one can produce single photons, detect them, and make observations on them without destroying them in the process. Since single photons carry very small amount of energy, the techniques for detecting them requires some mechanism of amplification. We will not go into details about this important topic, instead, we will describe the wave/particle duality of light in this subsection.

One can use single photons to conduct experiments that demonstrate wave-like properties as well as particle-like properties of photons. The particle-like properties of photon is demonstrated by single clicks of the detector when individual photons from a source arrive at the detector. Now, let us see how a photon behaves in a situation where we try to study wave-like property, such as interference, with a single photon.

Young's double-slit experiment is an ideal experiment for studying wave-like properties. Let us recall basic aspects of the Young's double-slit experiment which is discussed in more detail in an optics book. A point source of light is placed in front of a screen with two narrow slits and there is a screen behind the slits. Waves from the source arrive at the slits and emerge from behind the slits. The two coherent waves, one from each slit, travel to the screen where they interfere. The intensity of light is strongest at the place where they interfere constructively and intensity is zero where they interfere destructively.

Suppose you conduct a Young's double-slit experiment in which the source a single photon source. What will you see at the screen? An arrangement for conducting a single-photon interference by using a very dim light source is shown in Fig. 2.11. The light from a low power lamp is passed through a narrow slit and a filter. The light is then further dimmed by passing through a narrow slit marked single slit in the figure.

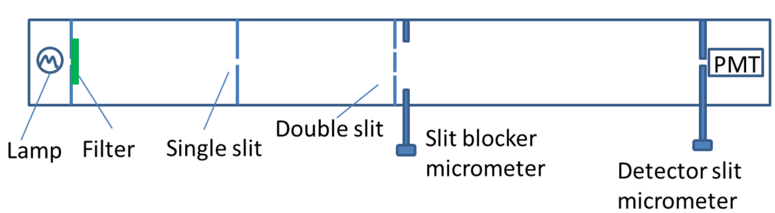

Figure 2.11: Schatics of the apparatus for conducting a single-photon interference experiment.

We first make sure that there is only one photon to the right of the single-slit at any given time. We do this by the count rate from the photomultiplier tube. The distance from the single slit to the detector is approximately 0.5 m. A photon will take 1.7×10^{-9} sec. If we get only a few hundred photons arriving at the detector per second we will assume that there is a single photon in the chamber at any time.

When the double-slit plate is placed in between the single slit and the detector, a photon coming out of the single slit travels to the double-slit. When the photon arrives at the slits, which slit the photon will go through? If it goes through one of the slits, then behind that double-slit plate there will be only one source, not two sources. Without two sources, there should not be any interference observed at the detector.

We fix the detector at one location on the screen and observe the reading for single photons sent through the double slit. The event rate from the photomultiplier in counts per second for various positions of the detector are then plotted as shown in Fig. 2.12 by the data provided for a similar instrument by TechSpin. You can see that, although for any one photon, you either see an event at the detector or you don't, but when you compile the result for the entire run, an interference pattern emerges in the data that has the maxima and minima at expecte places for the given wavelength of the photon and the slit separation.

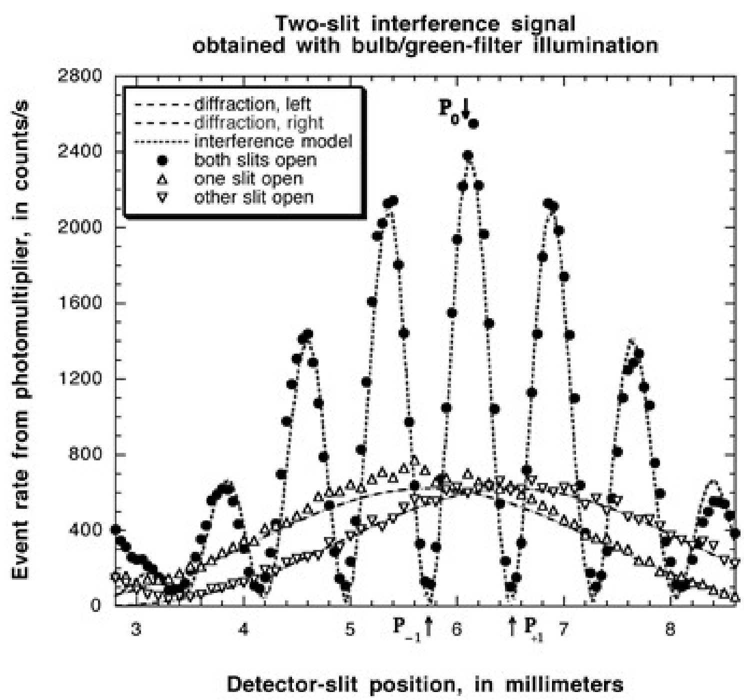

Figure 2.12: Photon counting at the detector for double-slit shows an interference pattern even though only one photon is in the chamber at any time and only one photon is observed at the detector. Similarly, the diffraction of a single photon through a single-slit shows the diffraction pattern as if a single photon were a wave. Credits: http://www.teachspin.com/instruments/two_slit/experiments.shtml.

Fig. 2.12 also shows that if you replace the double-slit by a single slit you get the diffraction effect.

Since, we do not have any explanation of the interference pattern without two sources from two slits interfering at the screen, it is believed that a single photon arriving at the slits goes through both slits, which is possible only if a photon is a wave. A single photon, which acts as a particle in the photo-electroc effect and Compton effect is acting as a wave in the Young's double-slit experiment!

Strangely, in the same experiment, a photon takes up two personalities: at the source and at the detector, it is a particle, but in-between the source and the detector, the photon acts as a wave! This experiment demonstrates the wave-particle duality of photons. It turns out that the dual personality is not limited to photons, but every particle in nature has this dual personality.