# 11.2: Quantum Interference

Thomas Young showed in 1803 [7] that light traveling through a pair of parallel slits will produce an interference pattern that follows Bragg's Law for diffraction. This was a huge problem to the existing Newtonian theory of light, as place CityNewton had postulated that light is, in fact, a stream of particles. With the advent of a quantum theory, light was postulated to have a dual nature, having properties of both particles and waves. This dual nature, of course would be applicable to the description of matter as well according to Louis de Broglie. At this point, things started to get really interesting. But before we go into that, let's think about the two-slit experiment in terms of the Heisenberg Uncertainty Principle.

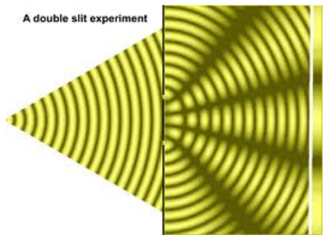


Figure 11.2.1

Recall that the Uncertainty principle states that there is a small minimum value for the product of the uncertainties of position and momentum.

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

This concept can be used to describe why a light wave is diffracted by a slit. As the photon or other wave-particle passes through the slit, the uncertainty of the position of the wave-particle is basically given by the size of the slit. The uncertainty in momentum then allows for the spreading of the wave-particle spatially. This is illustrated in the diagram. This interpretation is very useful in understanding how Einstein used this experiment as a criticism of the Uncertainty Principle and of the Quantum Theory itself.

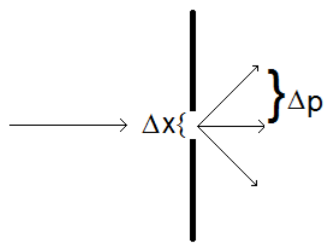


Figure 11.2.2

In 1924 [8] [9], Louis de Broglie proposed a wave description of all matter by proposing his famous wavelength relationship

$$\lambda = h/p$$

His predictions that matter-wave interference could be observed was confirmed in 1927 in independent experiments by George Thomson, who observed diffraction patterns in electron beams passing through thin metal films [10] and by Clinton Davison and Lester Germer, who observed electron diffraction on an electron beam focused on a crystalline nickel metal surface. [11] Thomson and Davisson shared the Nobel Prize in Physics in 1937 for these discoveries.

While the observation of interference of matter waves gave a great deal of credibility to the emerging quantum theory, Einstein was still troubled. In a series of interactions with Bohr, Einstein would propose thought experiments which he believed would uncover an inconsistency in the quantum theory by violating the Heisenberg Uncertainty Principle. Bohr would then consider the experiment and, in particular, the apparatus that would be used to make the measurements Einstein had proposed. Then, in presenting the "apparatus" to Einstein, Bohr would explain the flaw in Einstein's reasoning and how such a measurement could not violate the predictions of quantum mechanics.

One such exchange occurred over the concept of the "two-slit" experiment. In this experiment, a beam of electrons travels through a screen before arriving at a detector. In the screen, there are two slits through which the beam may pass. Each of these slits will diffract the beam, and lead to an interference pattern as the beam hits a detector screen. The diffraction is confirmed by the interference pattern observed on the detector.

To make matters even more interesting, if one slit is blocked, the result is the disappearance of the interference pattern. Instead, the recorded signal is consistent with the electrons traveling through the single unblocked slit.

For light waves, this phenomenon was well understood, thanks to the experiments of Young. But for matter waves, the picture becomes someone bizarre. There is not much of a problem if one considers what happens when the beam is turned on continuously. In this case, there are plenty of electrons making the transit and it is easy to imagine each as having a wave nature which can interfere with all of the other electrons making the transit.

The real excitement happens when the electron source is slowed down so that only one electron is making the transit at a time. If the resulting signals generated when the electrons reach the detector are integrated, over time an identical interference pattern emerges! “How can that be?” I hear you cry. And the question would indeed be very profound.

One explanation is that each electron traverses the distance from the gun through the slits by taking both possible pathways. This explanation is equivalent to saying that the electron becomes delocalized as soon as it leaves the source, takes all possible pathways to the detector and then becomes localized once again when it interacts with the detector, revealing its final position. Such an explanation would be very problematic to a person clinging to the philosophy of Determinism.

Einstein’s description of the phenomenon provided an important piece of the puzzle in terms of probing the limitations of quantum theory. Einstein argued that a particle passing through a slit would only have its path altered if it imparted some momentum to the screen containing the slit through a collision. That collision would have to cause the screen to move a tiny amount (due to conservation of momentum.) And if that movement could be detected, then one would then simultaneously know both the position of the particle (as it passed through the slit) and its momentum (due to the momentum imparted to the slit itself.) And this would create a violation of the Heisenberg Uncertainty principle.

Bohr’s response was quick and decisive. He pointed to the fact that Einstein had only attempted to apply the Uncertainty Principle to the wave-particle that passed through the slit and not to the slit itself. In fact, the uncertainty in the momentum of the slit will be the same as the uncertainty in the momentum of the wave-particle (since similar methods are used to measure them.)

$$\Delta p_{slit} = \Delta p_{wp}$$

Further, the uncertainty of the position of the wave-particle is equal to the uncertainty of the position of the of the slit.

$$\Delta x_{slit} = \Delta x_{wp}$$

Additionally, the slit itself must satisfy the Uncertainty Principle in that

$$\Delta x_{slit} \Delta p_{slit} \geq \hbar/2$$

simple substitution shows that if the slit is governed by the Uncertainty Principle, then the wave-particle must be as well.

$$\Delta x_{wp} \Delta p_{wp} \geq \hbar/2$$

This argument does not prove that quantum mechanics is correct, but it does show that it is self-consistent.

Very recently, scientists have used a modified approach to the double-slit experiment to reopen the question. [12] In this experiment, laser light shines on a screen with two pinholes. A clever detection system is used that detects only those photons that pass through one of the pinholes (a particle-like behavior.) But at the same time, detecting wires are placed in the positions of the destructive interference fringes (where no light should fall), confirming that no light is detected in these dark fringes (which is a consequence of the wave nature of light.) As such, the experiments demonstrate that light can show both the wave and particle nature simultaneously – something that Bohr had predicted to be impossible based on the idea of complementarity. Clearly, the debate continues and forms the subject of current research.

Bohr and Einstein would have several of these types of debates over the course of the late 1920s. Each time, Einstein would propose a thought experiment which he believed would violate the Uncertainty Principle, and each time Bohr would counter with a demonstration that, in fact, there was no violation at all. It seemed that Einstein was defeated. However, that was far from the case!

However, before exploring Einstein’s next move, let’s consider another experiment that shows the strangeness of quantum mechanics. It will be useful in framing a discussion of Einstein’s next move.

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