# 15.7: A New Paradigm

At this point it would seem fair to ask the question "Is light a wave, or is light a bunch of photons"? How could Maxwell's equations describing light as a continuous disturbance be compatible with the Planck-Einstein approach of treating light as a particle? They aren't. Is there compelling evidence for both models? There is. The wavelike nature of light has been experimentally confirmed many times, and much of the telecommunications industry is based on the wavelike nature of light. Likewise, the particulate nature of light has been verified in countless experiments, despite its controversial nature. How can we reconcile these different approaches to the same phenomenon?

To further complicate matters, we return to the description of an electron. It is well documented that electrons are discrete objects. They have a set charge and a measurable mass. Atoms are typically ionized by removing electrons from the orbital shells, further emphasizing their discrete nature. However, in 1924 Louis de Broglie rearranged the photon momentum equation to show that any object having momentum should also be described by a wavelength. In its original form, the equation for the momentum of a photon is:

$$\mathrm{p} = \frac{h}{\lambda}$$

The de Broglie relationship is:

$$\lambda = \frac{h}{p}$$

This was used to suggest that electrons in atomic orbitals could be thought of as standing waves, and furthermore that all matter of a particulate nature could have corresponding wavelike properties. In essence, de Broglie thought that matter could be thought of as a collection of waves that traveled with a common speed and had an effective mass. Both of these properties depended on the energy of the 'particle' and this was connected to the work of Einstein in the preceding years.

In 1925 and 1926 Edwin Schroedinger used the particle-wave duality of electrons to develop a wave equation that described the motion of electrons. This became known as the Schroedinger equation and directly led to the later development of quantum mechanics as a robust area of physics exploration. There were discussions about how to 'prove' the wavelike behavior of electrons using diffraction effects. Interference and diffraction are characteristically wavelike properties, so having electrons display diffraction would validate their treatment as continuous waves instead of discrete 'lumps' of matter.

In 1927, the wave nature of electrons was confirmed by two different sets of diffraction experiments. As was discussed in the chapter about reflection and refraction, diffraction is a distinctly wavelike behavior. Having electrons display diffraction effects verified that electrons 'are' waves. These results were expanded upon in the 1930s with beams of helium atoms and hydrogen molecules. In both cases, the wavelike nature of atoms and molecules was confirmed. This indicated that wavelike behavior is not limited to electrons and is apparently a general property of matter at the microscopic scale.

Waves and particles are two very different models for physical systems. Waves obey wave equations, are continuous and vary over time. Waves display diffraction and wave interference effects. Water waves, seismic waves, radio waves, sound waves and more are all modeled using wave equations and all show exceptionally good agreement between the model and the experimental results.

Particles obey classical mechanics, have trajectories where their position and velocities vary over time and have a center of mass. They do not display interference or diffraction effects. Stars, planets, spacecraft, tennis balls, bullets and grains of sand can all be modeled as particles and again the experimental results validate this approach.

## So, Particle or Wave?

While this is a perfectly natural question to ask, it turns out that it is not a terribly useful question to ask. The answer depends on other factors. Sometimes small objects behave like waves and sometimes they behave like particles. Some quantum experiments show particle-like collisions when two objects interact, other experiments show wave-like diffraction and interference effects. As a sort of catch-all statement, physics is able to suggest that energy propagates from one point to another like a wave (with wavelengths, wave speeds and amplitudes), but interactions happen in a particle-like fashion (with momentum, kinetic energies and forces).

It may seem disconcerting to try and hold two contradictory models in our thoughts, but the question is less about truth and more about utility. The only question that is reasonable to ask is "will my model match the experimental evidence better if I treat this as a wave or as a particle?". We will need to practice the same sort of mental flexibility when we try and understand the workings of the nucleus. It turns out that a lifetime of physics experience on earth has little to offer when we try and understand the workings of things beyond our direct experiences.

As dismissive as it might appear upon first reading the statement, Neil deGrasse Tyson was correct in saying "The Universe is under no obligation to make sense to you." Whether or not it 'makes sense', the goal of science is to understand how things behave. If they behave in ways that seem intuitive and are easy to grasp, so much the better. If the behaviors are strange and unsettling to our preconceived notions, it is our duty to adjust our thinking.

*"It is far better to grasp the universe as it really is than to persist in delusion, however satisfying and reassuring." - Carl Sagan.*

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