Wave Particle Duality

HOME: The Physics of Bruce Harvey

Introduction

It is true to say that light exhibits both particle like properties and wave like properties. It is also true that at times particles particles exhibit wave like properties.

In quantum physics, the emphasis is on the observation and since it was conceived in the belief that classical physics was unable to explain such newly discovered phenomena, the concept of wave-particle duality was embraced with vigorous enthusiasm. Are we to really believe that the flight of cricket ball is influenced by probability calculations relate to a wave length of 10^{-34}, or can its path be rationally explained in terms of gravity, friction and fluid dynamics. In our unified theory, we seek to find rational explanations.

The idea that light consisted of particles dates back to Newton. The alternative theory that it is a form of wave motion is from the same period. Both theories explain refraction and reflection. Although diffraction patterns were observed in the era of Newton, it was not until 1803 that Young provided the mathematical analysis that proved that light was propagated by waves. This was further reinforced when Maxwell showed that light consisted of electromagnetic waves. A century after Young's dicovery of came the discovery of the photoelectric effect and the conclusion that light comes in discrete bundles of energy and that their energy content is determined by their frequency. For some reason beyond the author's comprehension, this was taken as evidence that light also existed as particles.

The problem comes from the fact that the word particle carries with it a lot of preconceptions. Every one can tell you that particles are hard round little things which have mass and bounce off each other and everyone can also tell what waves look like and that waves cannot exist by themselves, but need something like the surface of a pond or an ocean to wiggle. However unscientific these descriptions may sound, that is how our brains try to conceptualize them. The two ideas do not sit easily together, but that does not matter too much because our brains have also evolved to handle contradiction enabling communities to be bound together into effective fighting units by religion. When pressed to explain contradictions the priest simply invokes the word "mystery". Likewise the physics teacher resorts to this device. It is something beyond our comprehension. It is how things are. We call it wave-particle duality and it is a fundamental part of physics. So the students switch their brains into religious logic mode and contemplate the "mystery" in awe of the wonders of nature.

There is no room for such nonsense in our unified theory. Light comes in discrete bundles of energy which we call photons. We cannot see photons, but fortunately nature has provided us with an analogy. There are occasions when the weather is still and the sea flat. If it happens that a few days ago and many thousands of miles away, there was a severe storm, we will see wave trains. At any one time, about seven significant crests are visible. As the wave train moves forward, so the crests move slowly forward within the wave train, each one forming at the rear, moving through the wave train and then decaying at the front. The surprising thing is that the wave train is not very wide and while beautiful surf might be pounding one bit of beach, 100 metres to either side the sea will be flat.

In our unified theory, photons consist of a number of phases, each comprising a loop of magnetic flux and its accompanying electric flux. Particles such as electrons and quarks are nothing but electric flux with their accompanying magnetic flux. The only difference between an electron and a photon is the geometry of their electric and magnetic fields. They are both discrete bundles of electromagnetic energy.

We postulate that the manifestations of wave like and particle like behaviour result from two different solutions of Maxwell's equations. The traditional solution had electric and magnetic flux stationary in the æther, but varying in flux density. Our alternative solution involves the electric and magnetic flux moving together through the background. We postulate that the traditional solution only exists in nature as a pertabation of existing stationary fields. We further postulate that there is an interaction between these two solutions which is responsible for the phenomena we identify as examples of wave-particle duality.

Single Photon Interference

The wave like properties which explain interference patterns were until recently believed to require coherent light. Coherent light results from the fact that atoms are very reluctant to emit photons spontaneously. Most photons are emitted through stimulated emission triggered by a passing photon which causes the emitted photon to be parallel and in phase with itself. A process which is exploited to its full in the laser. Single photon interference was first suspeced to have occurred in a Michelson stellar interferometer used to measure the diameter of stars. Telescopes have too small an aperture to give clear images of stars. Instead, they produce a diffraction pattern called an Airy Disc. If the aperture of the telescope is covered with a screen so that light only enters through two apertures at opposite sides of the lens, a second diffraction pattern is seen within the central disc of the Airy pattern. Given the right relationship between the diameter of the star and the distance between the apertures, the diffraction pattern disappears. Michelson improved on this by using mirrors to get a greater effective separation of the apertures. The use of long exposures for distant stars and the large separation of the mirrors led to the conclusion that only one photon was being detected at a time.

Any good university will include a demonstration of single photon interference as part of the students' laboratory work. If we are trying to prove that single photon interference is a real phenomena, then the first thing to do is to look for light sources which cannot produce coherent light. On no account should any patent apparatus using an HeNe laser to produce polarised coherent monochromatic light be used.

Single photon interference can be demonstrated using light from an incandescent bulb and a gel filter with the Young's slit apparatus. But just to be certain, the apparatus should also be able to image single photons being reflected from the metal components which form the two slits. We must be sure that photons are not arriving in showers.

It would also be interesting to replace the twin slits with various types of diffraction grating to see if the sharpness of a multiple beam image could be repeated.

In the author's opinion, single photon interference is not proven to his satisfaction as a general principle. There are in his opinion two possible explanations as to why it is observed. One explanation is that light is indeed propagated as transverse waves and that the orbiting electron is capable of adsorbing radiation over a period of time. This is the classical concept of the electron as an oscillator. In the author's opinion, the relationships between orbital frequencies and photon frequency are not simple enough for this to occur.

The other explanation is that the atoms at the edges of the slits effect a net negative electric charge along their edges and that the flux resulting from this excess responds to the electric field induced by the motion of the photon's magnetic flux. This results in an energy transfer from the photon to these fields which affects the motion of the electron enabling the energy to transfer through each slit from the near side to the far where is propogates away from the slits forming a diffraction pattern. Now the photon has to recover this energy and as it does so, the diffraction pattern guides its path.

De Broglie's Bohr Atom *and the wave like electron*

Because the quantisation of magnetic flux had not been discovered, Bohr's model of the hydrogen atom was without any logical explanation as to why only certain orbits were allowed.

De Broglie proposed an explanation. The electron had wave like properties and each allowed orbit corresponded to a given number of wavelengths.

The solutions for the Bohr atom give:

$$r = \frac{n^2 \varepsilon_0 h^2}{\pi m e Z} \qquad \nu = \frac{m e^2 Z^2}{4 n^3 \varepsilon_0^2 h^3} \qquad \mathrm{v} = 2\pi r \nu$$

From these, we can calculate the kinetic energy and momentum p of the electron:

$$KE = \frac{1}{2} m \,(2\pi r \nu)^2 = \frac{m e^4 Z^2}{8 n^2 \varepsilon_0^2 h^2}$$

$$p = m \left(2\pi r \nu\right) = \frac{m e^2 Z}{2 n \varepsilon_0 h}$$

We can also calculate the frequency and wavelength of the postulated wave:

$$\lambda = \frac{2\pi r}{n} = \frac{2n \varepsilon_0 h^2}{m e Z} \qquad f = n \nu = \frac{m e^2 Z^2}{4 n \varepsilon_0^2 h^3}$$

Now these four expressions are quite nasty looking beasts, but closer examination reveals that the expressions for the kinetic energy and frequency are very similar and that the momentum is similar to the reciprocal of the wavelength. Indeed, they lead to two very simple equations:

$$\lambda = \frac{h}{p} \qquad f = \frac{2\,KE}{h} \quad \text{or} \quad f = \frac{E}{h}$$

In fact, we make them even simpler if we note that $|PE| = 2KE$ and call it E. This is a good a way as any of loosing an unwanted 2 and quite within the spirit of the times.

With such loose thinking, it is but a simple step to turning the E into Einstein's $E = m c^2$. Suddenly, we have lost sight of the atom and are thinking about free electrons. The basic concept of a vibrating string which fuelled de Broglie's imagination to postulate that the orbit consisted of a whole number of wavelengths has now been replaced by one of a wave train in the ocean. The definite position of the electron has been replaced by a series of peaks and troughs of a "pilot wave". Surely E must be a relativistic energy and we end up with deducing that the velocity of the pilot waves is that given in text books as:

$$w = c\sqrt{1 + \left(\frac{m_0 c}{p}\right)^2}$$

We find the pilot waves travelling faster than the speed of light. This is pure fantasy, but that does not mean that electrons cannot behave in a wave like manor.

Once upon a time, electronics depended on vavuum tubes and electrons might be accelerated by a modest 100V to about 2% of the speed of light. At this speed, electrons have a de broglie wave length of the same order of size as the spacing between atoms. In a transmission electron microscope working at 100Kv, the electrons have a velocity a little over half the speed of light, the de Broglie wavelength is more than 3 orders of magnitude smaller than the size of an atom.

A convincing demonstration that electrons behave as waves would be able to produce identical interference patterns from the same diffraction device using either light or electrons. Electrons with a velcoity of 1,250 $\mathrm{ms^{-1}}$ have a de Broglie wavelength approximately equal to that of sodium yellow. The only problem is that it might be technically very challenging to produce a beam of such slow electrons because only 4μV will accelerate an electron to that velocity. This is significantly small compared with the potential field surround an individual electron which is of this magnitude at a distance of one millimetre. Electrons would have to pass through the apparatus one at a time and the resulting pattern be compared with single photon interference.

Very striking interference patterns can be produced when a beam of electrons hits the surface of a crystal at a very small angle of incidence. For 300KV electrons, an angle of 0.28 degrees will produce good results comparable with the multiple beam interference patters of X-ray diffraction. If these near light speed electrons behaved as particles, they would only suffer very slight deviations to their path through meeting orbital electrons and only be significantly deflected on passing near a nucleus. When we calculate the greatest of the closest distances of approach, due to the very small angle of incidence, this is 0.005 times the lattice spacing and produces a deflection of at least about 6 degrees. What we observe is a reflection at the same angle of incidence of 0.28 degrees. Therefore the electrons are not behaving as particles.

Our unified theory does not allow any explanation which is inconsistent with our understanding of the nature of matter and fields and their interaction. The first step is to calclate the speed of 300KV electrons which is 0.777c. This is compatible with the speed at which signals can be transmitted down a wire, so it is not impossible that the electrons are inducing the kind of EM wave associated with the limit of signal speed in a conductor.

The second step is to consider the de Broglie wavelength which for a 300KV electron is 1.97×10^{-12}. We can calculate the energy of a photon of this wavelength in electron volts:

$$E = \frac{c\,h}{\lambda}\frac{1}{e} = 629.4\,KeV$$

This is just over twice the energy of the 300 KV electron. The direct comparison is inappropriate because the physical comparison of the electric and magnetic fields of a near light speed electron with those of a photon shows one striking dissimilarity. While the photon is 8 phases long, the electron's fields are essentially only 1 phase long.

While we are still a long way away from a complete explanation, we believe that there are sufficient grounds for believing that the kind of electron diffraction seen in this case is more likely to be caused by an electromagnetic process than by some mystic property of wavy-particle-ness.

Wave like behaviour of particles

Despite the vast number of applications of particle diffraction, the author remains unconvinced of the general validity of the de Broglie's Postulate. Perhaps his expectations were raised too high by studying under the worlds leading exponent of multiple beam interferometry, but in his mind, the images produced in support of de Broglie are all too diffuse.

Light produces interference patterns of high contrast. Multiple beam interference patterns are very sharp and allow high resolution. Examples include high resolution spectroscopy using a grating.

X-ray crystallography also produces sharp images of high contrast because the array of atoms in a crystal act in the same way as the multiple slits of a diffraction grating.

Obviously, we must take into account the ability of the wave-particles to produce coherence, so perhaps we should not expect the sharpness of a multiple beam image, but for light even single slits produce high contrast images.

Electron microscope resolution

The limit of resolution of optical instruments is well understood and known to depend on the wave length of the light. Electron microscopes overcome this limitation. Apart from focusing problems, the resolution of an electron microscope depends on the energy of the incident electrons. The de Broglie postulate gives a relationship between Planck constant *h*, wavelength λ and momentum *p*:

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

From this, it is inferred that the resolution depends on the wavelength of the electron thus confirming the de Broglie postulate.

This confirmation is based on false logic.

The limit of resolution can be explained very simply by assuming that the electron is a charged particle obeying the laws of Newton and Maxwell when allowance is made for the increase in mass at near light speed.

Quite simply, the distance of closest approach is limited by the fact that at this point, the potential energy is equal to the loss in kinetic energy. For normal reflection:

$$\frac{e^2}{4\pi\,\varepsilon_0\,r} = \frac{1}{2}\,m\,v^2 \qquad \Rightarrow \qquad r = \frac{e^2}{2\pi\,\varepsilon_0\,m\,v^2}$$

But if we consider the Electron Transmission Microscope, the loss in kinetic energy is only fractional giving:

$$r = \frac{e^2}{2\pi\,\varepsilon_0\,m\,(u^2 - v^2)} = \frac{e^2}{2\pi\,\varepsilon_0\,m\,(u + v)(u - v)}$$

The term $(u - v)$ now relates to individual electron trajectories, so the term $(u + v) \approx 2u$ becomes dominant in determining the resolving power.

If we put in some numbers for a ETM working at 100Kv, the electrons have a velocity a little over half the speed of light, the de Broglie wavelength is more than 3 orders of magnitude smaller than the size of an atom. Our analysis suggests a distance of closest approach two orders of magnitude smaller. It is obvious that if we are looking at atoms, the differences in predicted resolving power will not be observable.

It is apparent that the resolving power is limited by the difficulty in focusing the electrons to form an image.