Photon Structure and Behaviour

HOME: [The Physics of Bruce Harvey]

Introduction

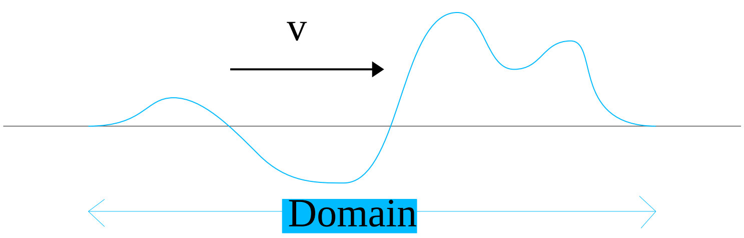
It is customary to just accept the photon as something which cannot be understood by common sense and expound upon the mysteries of wave particle duality with an almost religious fervour. We believe that this state of affairs has arisen because of the order in which discoveries were made. Dogma became fixed before the necessary information was available to unravel the mystery. The most important missing factor was the quantisation of magnetic flux.

We propose a model for the structure of a photon based on the assumption that it consists of quantum fluxoid loops of magnetic flux each permeated by a quantum of electric flux. Each phase has a single loop of magnetic flux varying as $1 - cos\left(\frac{2\pi x}{\lambda}\right)$ with all the phases of the same polarity. The differentials of this function are the same as those of the traditional sinusoidal solution of the wave equation ensuring identical induced interactions. We propose an electric quantum fluxoid of $\frac{1}{6}$ of the charge on the electron $\Psi_0 = \frac{1}{6}e$ which is consistent with the charge on the electron and quarks. A photon 8 phases long would have an energy content of $h\nu$ which we consider to be consistent with ocean wave trains, though we have not yet provide a mathematical basis for it.

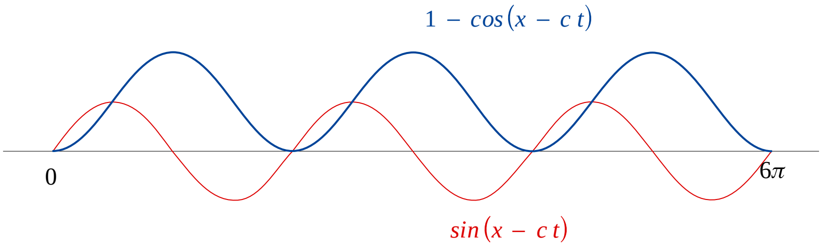
The first obstacle we meet in trying to solve this problem is the fact that Maxwell's wave equation has always been solved in terms of sine and cosine functions. The integrals which give us the flux content of a phase involve $\int sin\,\theta$ and those which give energy content involve $\int sin^2\theta$. Only one of these is a multiple of π and our answers will always contain an unwanted π. The second is that it is very rare to find any account taken of the geometry of the magnetic flux necessary to satisfy Maxwell's equation $Div\,\vec{B} = 0$. We have to look for models of the field geometry of photons and find a solution to the wave equation which allows an integer fraction of $h\,\nu$ for the energy content per phase.

Wave equation solutions

We have shown that the wave equation in one dimension which takes the form $\frac{d^2}{dx^2}f(x,\,t) = v^2\,\frac{d^2}{dt^2}f(x,\,t)$ has a solution which is any single valued, twice differentiable function of $(x + v\,t)$ with smooth tails.



After a long process of trial and error, the function $1 - cos(x + v\,t)$ emerged as the best candidate. Here we see it together with its differential $sin(x - c\,t)$ defined over the domain $0 \leqslant x - c\,t \leqslant 6\pi$ travelling from left to right at the speed of light.



It behaves well under integration and differentiation;

$$\int_0^{2\pi} 1 - cos(x - c\,t)\;dx \;=\; 2\pi; \qquad \int_0^{2\pi} (1 - cos(x - c\,t))^2\;dx \;=\; 3\pi$$

Since these are both simple multiples of the interval, we will have no difficulty finding a solution which gives the flux as an integer multiple of Φ_0 and the energy as $h\,\nu$.

In particular, its differentials are those of a sinewave:

$$f \;=\; 1 - cos(x - c\,t); \qquad f' \;=\; sin(x - c\,t); \qquad f'' \;=\; cos(x - c\,t)$$

so that any fields induced by its passing will have the required sinusoidal oscilation. Maxwell's derivation of the wave equation is only a partial solution to his equations. Although f is a function of both position and time, we may swap to the co-moving co-ordinate system where x is measured relative to the phase, t vanishes and $f\,(x - c\,t)$ becomes simply $f\,(x)$.

Energy of a photon

A photon consists of electric and magnetic flux everywhere orthogonal to each other and its path[1]. The flux densities are governed by:

$$H \;=\; c\,D \qquad E \;=\; c\,B \qquad B \;=\; \mu_0\,H \qquad D \;=\; \varepsilon_0\,E \qquad c^2 \;=\; \frac{1}{\varepsilon_0\,\mu_0}$$

The energy densities of electric and magnetic fields are $\frac{1}{2}\vec{D}\cdot\vec{E}$ and $\frac{1}{2}\vec{B}\cdot\vec{H}$ respectively. Simply by substituting $E = c\,B$ and $H = c\,D$, we get an expression for the energy density of the flux of a photon.

$$\text{Energy density} \qquad \frac{H\,B}{2} + \frac{E\,D}{2} \;=\; \frac{c\,D\,B}{2} + \frac{c\,B\,D}{2} \;=\; c\,B\,D$$

We consider a circular loop of magnetic flux Φ of rectangular cross section orthogonal to the direction of motion. If r is the radius of the loop, t its thickness (parallel to r) and w its width (in the direction of motion) and t is small compared to r. The motion of the loop generates an electric field with flux Ψ. From the geometry of the loop:

$$\text{Energy density} \qquad c\,B\,D \;=\; c\,\frac{\Phi}{w\,t}\,\frac{\Psi}{2\pi\,r\,w}$$

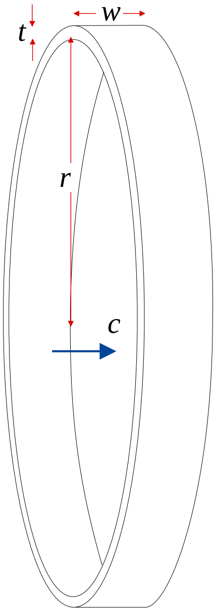
$$\text{Volume} \qquad \;=\; 2\pi\,r\,w\,t$$

$$B \;=\; \frac{\Phi}{w\,t} \qquad\qquad D \;=\; \frac{\Psi}{2\pi\,r\,w}$$

The energy is:

$$\mathcal{E} \;=\; c\,\frac{\Phi}{w\,t}\,\frac{\Psi}{2\pi\,r\,w}\,2\pi\,r\,w\,t \;=\; \frac{c}{w}\,\Phi\,\Psi$$

[1] Though in the case of circularly polarisation, $\vec{B}$ may have a component in the direction of motion. We deal with this in the section on Circular polarisation.



Now for radio waves and light $\frac{c}{\lambda} = \nu$. So there is a fundamental relationship between energy and frequency for a certain flux content per phase.

If t is not small compared to r, then we divide the loop into a lare number of thin concentric loops each of magnetic flux content $\delta\mathbf{\Phi}$. Each thin loop will still be permeated by the same electric flux $\mathbf{\Psi}$. For each thin loop:

$$\delta\mathscr{E} = \frac{c}{w}\,\delta\mathbf{\Phi}\,\mathbf{\Psi}$$

We may sum the energy of all thin loops and since c, w and $\mathbf{\Psi}$ remain constant:

$$\mathscr{E} = \frac{c}{w}\,\mathbf{\Phi}\,\mathbf{\Psi}$$

regardless of the thickness of the loop.

Let us now divide the loop into slices of thickness δw. Energy in each slice is:

$$\delta\mathscr{E} = \frac{c}{w}\,\mathbf{\Phi}\,\mathbf{\Psi}\,\frac{\delta w}{w}$$

The total energy is the sum of the energies of the slices and we can form an integral:

$$\mathscr{E} = \frac{c}{w}\int_0^w \mathbf{\Phi}\frac{\mathbf{\Psi}}{w}\;dx$$

In this integral, $\frac{\mathbf{\Psi}}{w}$ is a linear flux density. We may replace it with a function of x so long as the total flux content is preserved. However, the linear flux densities of the electric and magnetic flux must vary in the same way.

$$\mathscr{E} = \frac{c}{w}\int_0^w \mathbf{\Phi}\,f(x)\mathbf{\Psi}f(x)\;dx \qquad \int_0^w \mathbf{\Psi}f(x)\;dx = \mathbf{\Psi}$$

As discussed above, the function $1 - \cos\theta$ has the desired properties to obtain a solution. We express $\theta = \frac{x}{w} 2\pi$ in terms of the distance x measured relative to the phase; then:

$$\mathcal{E} = \frac{c}{w} \int_0^w \Phi \Psi \left(1 - \cos\left(\frac{x}{w} 2\pi\right)\right)^2 dx$$

$$\mathcal{E} = \frac{3c}{2w} \Phi \Psi$$

The variation in flux density according to the function $1 - \cos\theta$ has introduced a factor of $\frac{3}{2}$ modifying our original result for a ring of uniform flux density over its length.

The only physical dimension is w which is in effect the wave length. This allows the cross section of the photon to form almost any shape consistent with a magnetic flux content of Φ_0 per phase. We shall for simplicity assume that each phase is a cylinder with a very small hole around its axis and the physical form of the photon to be a number of phases. The field strength along the length of the cylinders is given by the above function. Each cylinder contains one quantum fluxoid $\Phi = \Phi_0$ of magnetic flux and one quantum of electric flux $\Psi = \Psi_0$. An electric quantum fluxoid of $\Psi_0 = \frac{1}{6}e$ would explain the charges of the U and D quarks, the flux of the D quark consisting of two hemispheres, that of U consisting of 4 three sided segments and that of the electron consisting of 6 four sided segments. This gives an energy per phase of:

$$\mathcal{E} = \frac{3}{2} \Phi_0 \frac{e}{6} \nu = \frac{1}{8} 2\, e\, \Phi_0\, \nu = \frac{1}{8} h\, \nu$$

We conclude that a photon 8 phases long with each phase consisting of a single loop of flux varying in flux density as $(1 - \cos\theta)$ will have an energy content of $\mathcal{E} = h\,\nu$. This is consistent with the observation that ocean waves travelling thousands of miles from a storm sort themselves out into well ordered wave trains of seven significant crests.

Shape of a photon

Photons cannot squeeze through holes smaller than their wavelength. This suggests a limit to the outer diameter of the photon. A photon would therefore approximate in form to a cylinder one wavelength in diameter and eight wavelengths in length. In the above analysis, the radius r of the flux loop cancels out of the equations. The energy content and the relationship $\mathcal{E} = h\,\nu$ are independent of the radius of the loop. However, when we work out the magnetic flux density, it becomes apparent that rather that a thin walled pipe, we are dealing with an almost solid cylinder with a very narrow hole though its centre. This is comforting because one of the big mysteries of the photon is how such a big structure can interact with an orbiting electron in an atom.

We can now integrate over the thickness of a flux loop of inner radius a and outer radius $\frac{1}{2}\lambda$ to find the flux content. The flux density varies over the length of the flux loop, but $\int_0^{2\pi} 1 - \cos(x - c\,t)\, dx = 2\pi$ so we can use an average value of 1. The (average over the length) electric flux density D varies with radius:

$$D = \frac{\Psi_0}{2\pi\, r\, \lambda} \quad ; \quad B = \mu_0\, c\, D \Rightarrow B = \frac{\mu_0\, c\, \Psi_0}{2\pi\, r\, \lambda}$$

$$\Phi_0 = \lambda \int_a^{\frac{\lambda}{2}} B\, dr = \lambda \int_a^{\frac{\lambda}{2}} \frac{\mu_0\, c\, \Psi_0}{2\pi\, r\, \lambda}\, dr$$

This is not a nice integral and we must make use of the fact that $a \lll \lambda$, integrate to an upper limit of $a + \frac{1}{2}\lambda$ and expand the result as a power series in $\frac{a}{\lambda}$ to get:

$$a = \frac{\mu_0 \, c \, e}{24\pi \, \Phi_0} \lambda$$

For green light $a \cong 2 \times 10^{-10} m$.

That is the same order of size as an atom and explains how a photon which is of the order of 500 times bigger than an atom can interact with it.

Mass and momentum

In Modern Physics, mass appears as a fundamental property of particles without any further explanation. When photons exhibit the property of mass, it seems almost magical. However, if our starting point is Lorentz's theory of electromagnetic mass, the comparison becomes obvious.

Moving elementary charged particles generate a magnetic field which contains energy. To accelerate an electron, we must do work to supply the increase in energy. The electron appears to be resisting the accelerating force and we say it has the property of mass, but the physical reality is that an electromagnetic interaction results in the electron possessing kinetic energy. Inertial mass is the mathematical artefact associated with the real physical entity of kinetic energy stored in a magnetic field. But the energy stored in the magnetic field is directly proportional to the energy stored in the electron's electric field. The mathematical artefact we call mass is directly related to the real physical entity of the energy content of the electric field of an elementary charged particle.

An accelerating force acts over a distance and for a time, the two being related by the integral over time of the velocity. We say the action $force \times time$ results in a change in momentum. Momentum appears to be a fundamental property of nature because it is conserved. However the law of conservation of momentum can be derived very simply from the law of conservation of energy. We should therefore regard momentum as being associated with kinetic energy. That is to say that in a collision in which momentum is conserved, the actual physical processes involved are always those of energy transfer.

Let us now compare an electron and a photon. Both have electric fields. The electric fields of both generate magnetic fields by virtue of their velocity and both have energy stored in their magnetic fields. In the case of the electron, we call that energy its kinetic energy. We might be tempted to say that the energy in the magnetic field of a photon is kinetic energy, but that is only half the story. What happens when we stop an electron? Two things; (i) its kinetic energy is used doing work against the resisting force and (ii) we are left with a stationary electron. When we stop a photon, we are left with nothing. All of its energy is adsorbed. Therefore the energy a photon possesses by virtue of its motion is contained in both its electric and magnetic fields.

It is therefore logical to equate the kinetic energy $\frac{1}{2} m v^2$ of an electron with the total energy $m c^2$ of a photon.