Feynman's QED

HOME: The Physics of Bruce Harvey

QED, that is Quantum Electro Dynamics is a collection of theories covering a wide range from the various forces between particles to the reason photons travel in straight lines. Here we take issue with only one of these theories, that which seeks to account for the force between electrons.

The force

We want to examine the idea that the force between elementary charged particles is due to the exchange of virtual photons. We will limit ourselves to the case of two electrons because we know that real photons possess momentum and can therefore expect the exchange between electrons to impart momentum and push them away from each other.

Consider two electrons a distance r apart. Classical theory predicts a repulsive force F which each electron exerts on the other given by:

$$F = \frac{e^2}{4\pi \varepsilon_0 r^2}$$

If this force is conveyed by the exchange of virtual photons travelling at c, the speed of light, which borrow energy from some unspecified source for a limited time under the uncertainty principle. The time for which the energy ΔE must be borrowed is:

$$\delta t = \frac{2r}{c}$$

The uncertainty principle states that $\Delta t \, \Delta E = \frac{\hbar}{2}$ ("h bar") and because it takes us in the right direction, we will use this version on the grounds that lots of photons will be exchanged and must be summed statistically, so we should be using standard deviation.

$$\therefore \quad \Delta E = \frac{\hbar}{2\,\Delta t} = \frac{\hbar c}{4r}$$

The photon is said to have a mass of $\frac{\Delta E}{c^2}$ and so it transfers momentum $\frac{\Delta E}{c^2} c = \frac{\Delta E}{c}$. In fact each virtual photon conveys this change in momentum, so the receiving electron gets an impulse of $\frac{\Delta E}{c}$ from the photon it adsorbs and another impulse of $\frac{\Delta E}{c}$ as the equal and opposite reaction to sending a virtual photon back. Both electrons can initiate the process, so at any moment there are two virtual photons conveying an impulse between them. Therefore the rate of transfer of momentum is:

$$4\frac{\frac{\Delta E}{c}}{\frac{r}{c}} = 4\frac{\Delta E}{r} = \frac{\hbar c}{r^2}$$

The force is the rate of change of momentum so we find that:

$$F = \frac{\hbar c}{r^2} \qquad \text{not} \qquad F = \frac{e^2}{4\pi \varepsilon_0 r^2}$$

Now this is a bit disconcerting, perhaps we have made a mistake. At this point the theoretical physicist has a simple choice, he can reject the idea as foolish, or he can look for a fiddle factor. Basically, the problem is that there are a lot of nasty physical constants, namely $\hbar$, c, π and ε_0. These constants can be found in the fine structure constant $\alpha = \frac{e^2}{\hbar c 4\pi \varepsilon_0}$. So all we have to do is to multiply by α.

$$F = \alpha \frac{\hbar c}{r^2} = \frac{e^2}{\hbar c 4\pi \varepsilon_0} \frac{\hbar c}{r^2} = \frac{e^2}{4\pi \varepsilon_0 r^2}$$

So we can make it work if we introduce the idea that the probability of sending out a virtual photon is moderated by the fine structure constant.

To the author's mind, this is a double maths fiddle. First in choosing the $\Delta t \Delta E = \frac{\hbar}{2}$ version of the of the uncertainty principle and second in introducing the fine structure constant. But apart from this, the theory has other flaws.

Pull or push

It is easy to explain why virtual photons might exert a repulsive force because one of the classical experiments involves a paddle wheel mounted in a vacuum tube. When a beam of light is directed at the top of the paddles, the wheel turns demonstrating that light exerts a force. So far as the author is aware, no one repeating this experiment has ever managed to polarise or reverse energise a light beam in such a way as to cause it to turn the paddle wheel in the opposite direction. How then are virtual photons to exert an attractive force?

Moving electrons by the zillion

So far, we have only considered one pair of stationary electrons. Lets add a little spice and have them both moving.

If the electrons are in motion, then before one electron can send a virtual photon to the other, it needs to know where it will be when the virtual photon reaches it; both to get the direction right and also to borrow the right amount of energy. So we have to add another layer to the theory and invent a type of quantum wave which the electron sends out to explore for the other electron and give it the very special property that it will collapse back in time to give the answer when and where it is needed. We have to accept both the existence of these mysterious waves and the fact that can travel both forwards and backwards through time.

The second problem is that if we look at any real situation, say sticking a balloon to the ceiling by charging it with static electricity, there are probably of the order of 10^{12} extra electrons on the surface of the balloon not to mention the 10^{24+} orbiting the atoms of the balloon. This means that each electron is going to have of the order of 10^{12} virtual photons to send out every few nanoseconds. That requires a lot of computation and bookkeeping.

Wavelength of a virtual photon

We are all used to Feynman diagrams with nice wavy lines indicating the photon. They look very wavelike. But photons have a wavelength given by the relationship $E = h\nu$ between energy and frequency.

$$h\nu = \frac{\hbar c}{4r}$$

$$h\frac{c}{\lambda} = \frac{\hbar c}{4r}$$

$$\lambda = 8\pi r$$

The wavelength of the virtual photon has to be over 25 times the distance between the electrons! Those wavy lines should not be so wavy.

The impossible hydrogen atom

Yet another problem arises when we consider how the electron is bound within the atom. Because the correct answer is only obtained by introducing the fine structure constant as a moderating probability, the time between the exchange of virtual photons becomes significant. If we use the Bohr model of the hydrogen atom as an indication of the size and time scales:

$$\frac{2\,r}{c}\,\frac{1}{\alpha} = 4.838 \times 10^{-17} \qquad \frac{1}{\nu} = 1.520 \times 10^{-16}$$

We find that we might expect about 3 virtual photons to be exchanged in the quantum mechanical equivalent of an orbit. Now this exchange is moderated by a probability, so it should produce a Poisson distribution. It does not need any sophisticated calculations to predict that within few nanoseconds a period of time between exchanges is going to be long enough for the electron to escape!