

# A First Introduction to Quantum Behavior

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## **Abstract**

The physics curriculum in England and Wales has a requirement to introduce quantum phenomena to students in the first year of the two-year pre-university physics course in schools. Usually this means discussing the photoelectric effect, with a few words about “waves or particles”. In the innovative course “Advancing Physics” we take a more fundamental approach, following Feynman’s “many paths” formulation of quantum physics. The experiences of teaching this material for the past five years are discussed, together with difficulties it has thrown up.

## **Introducing quantum behavior: a national requirement**

In England and Wales, all “A-level” Physics courses – that is, high school physics courses leading to University entrance – are required to introduce the quantum behavior of photons and electrons. For the innovative course *Advancing Physics* (Ogborn & Whitehouse 2000) we decided to base our approach on Richard Feynman’s remarkable small book “QED” (Feynman 1985), in which he describes in the simplest possible terms his ‘sum over histories’ or ‘many paths’ approach to quantum mechanics. Others have tried something similar (see Hanc et al 2005).

## **The Feynman approach in essence**

‘...Dick Feynman told me about his ... version of quantum mechanics. “The electron does anything it likes,” he said. “It just goes in any direction at any speed, forward or backward in time, however it likes, and then you add up ...” I said to him, “You’re crazy.” But he wasn’t.’

Freeman Dyson

Feynman’s big idea, starting with his 1942 doctoral thesis (Brown 2005), was to track all the space-time paths available to photons or electrons in a given situation. Every possible path is associated with a quantum amplitude. To find the probability of an event, you add up (taking account of phase) the amplitudes for all possible paths leading to that event. The probability is then given by the square of the amplitude, suitably normalized. The phase of the amplitude is given by a result first noted by Dirac, namely that the number of rotations of the phase ‘arrow’ along a path is just the classical action  $S$  along the path, divided by the Planck constant  $h$ .

This alternative way of setting up quantum mechanics led to enormous simplification of calculations in quantum field theory, and is still today an essential tool for theoretical physics. Our concern, however,

is with the simplification and clarification it can bring to a first introduction to the quantum world.

### **Six steps in introducing quantum behavior**

We think of our teaching program in six steps:

1. random arrival
2. photon energy in lumps of size  $E = hf$
3. superposition of amplitudes
4. what is quantum behavior?
5. quantum behavior can explain ....
6. electrons do it too.

#### ***Step 1 Random arrival***

Perhaps the most important first experience of quantum behavior is to listen to a Geiger counter detecting gamma photons: “click....click. click.....click”. The key point is that the gamma photons arrive *at random*. The time of arrival of a photon is not predictable: the only thing we can know is the *probability* of arrival. Here is the first cornerstone of an understanding of quantum behavior: only the probability of events is predictable.

A well known set of photographs (Figure 1) illustrates the idea beautifully.

A more careful treatment would want to show that the arrival of photons follows a Poisson distribution, but this level of discussion is not available to us in this course, though we are working on it (Ogborn, Collins & Brown 2003a,b).

#### ***Step 2 Photon energy in lumps of size $E = hf$***

The next step is to measure the energy and frequency to arrive at an estimate of the Planck constant  $h$ . We suggest the use of a set of light-emitting diodes (LEDs), measuring the wavelength of the light they emit, and the minimum potential difference needed for light just to be emitted.

The point is to get across, as simply and directly as possible, that whatever happens in between emission and arrival, light is always emitted and absorbed in discrete amounts  $E = hf$ . Now we have to think about “what happens in between”.

#### ***Step 3 Superposition of amplitudes***

In *Advancing Physics*, the study of quantum behavior follows a study of the nature of light. There, the classical story of the development of the wave picture is told, from Huygens and Fermat through to Young and Fresnel. Thus students know that interference effects arise when there are alternative paths between emission and absorption events. Now we marry up this wave picture of superposition with the story of quantum behavior.

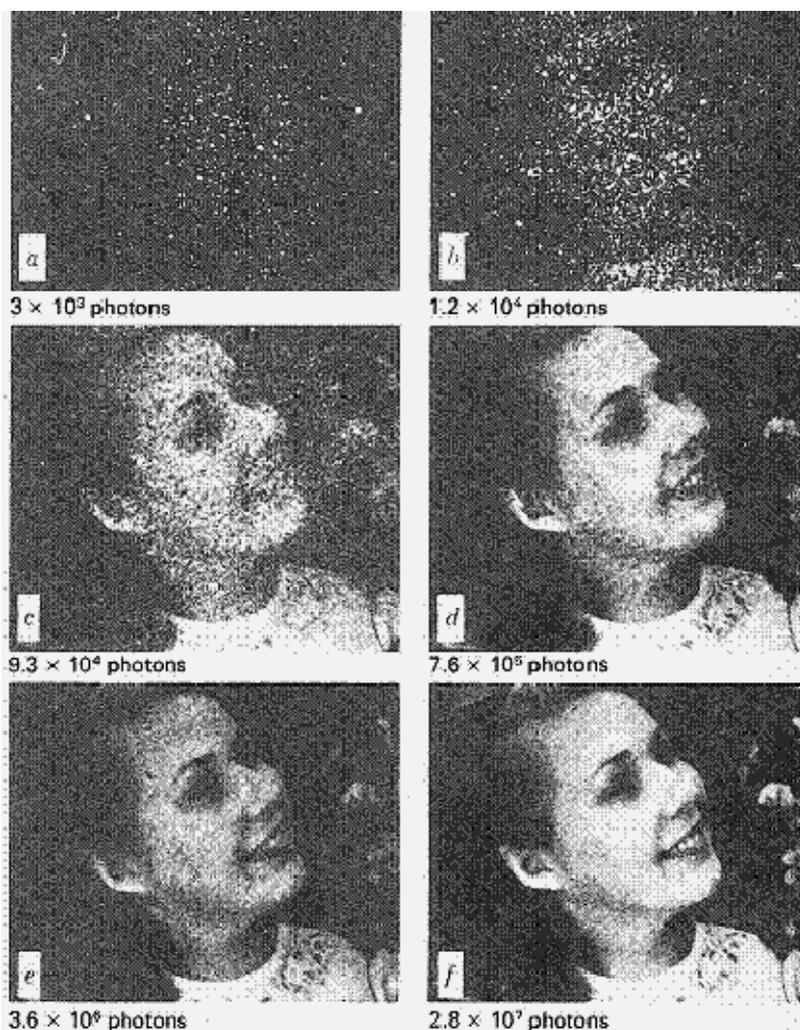


Figure 1: The same picture taken with progressively more and more photons. The photons arrive randomly, but with probabilities such that the picture gradually builds up.

The big idea of quantum theory can be put very simply. It is just: “steal the wave calculation but forget about the waves”. That is, associate with each path a phase ‘arrow’, and add up the ‘arrows’ to get the resultant amplitude from all paths.

This is just Huygens’ wavelet principle. But something new and essential is added. It is that the rate of rotation of the quantum arrow along a path is given by  $f = E/h$ . In this way, the results of the wave calculations of interference and diffraction patterns are all taken over. The novelty is to start with the photon energy  $E$  as given and fundamental, and to use  $h$ , the quantum of action, to translate it into a rate of rotation of phase.

Here we arrive at the heart of quantum behavior. In wave theory, the existence of a phase is a consequence of the nature of wave motion. In quantum thinking, the existence of a phase is rock-bottom fundamental. It is to be thought of as a given, not as a consequence.

#### ***Step 4 Quantum behavior***

We can now describe the behavior of quantum objects. For each possible path between initial and final discrete events, there is an ‘arrow’ (a phasor). For photon paths, the rate of rotation of the arrow between start

and finish is  $E/h$ . Add up the arrows for all the possible paths, tip to tail, to get the resultant ‘arrow’ for the pair of events. The square of the resultant ‘arrow’ is proportional to the probability of the pair of events.

Although initial and final events are localized, there is no reason to think of a photon as localized “in between”. Lumpiness in energy does not imply lumpiness in space. To say as Feynman does that the particles “go everywhere” is not to picture them as trying out all the possibilities one at a time. Part of the essence of “being a particle”, namely its continuing existence at a succession of places and times, has been taken away. Waves, of course, do “go everywhere”, but part of their essence has gone too. Their energy can no longer be divided into smaller and smaller amounts, without limit.

Not surprisingly, this account gives students difficulties. Like most of us, they naturally try to form as concrete a picture as possible. So, thinking of photons as particles, and imagining tracking each along a given path, they wrongly imagine them trying out all possible paths one by one. They tend to think of the rotating phasor, not as associated with the *path*, but as ‘riding on the back of a photon’ as it travels.

However, these difficulties are simply the difficulties of getting used to quantum thinking. A possible merit of the approach is that it brings them out so clearly, by denying that photons are some mixed-up approximation to waves and particles. Thus we present quantum behavior as itself, not as like something else. Its essence is that all possibilities contribute, superposing taking account of phase.

### ***Step 5 Quantum behavior explains...***

We conclude by offering students some comfort, by showing how quantum behavior explains some familiar things, in particular, the laws of reflection and refraction.

Figure 2 shows a diagram from Feynman’s book, illustrating how the law of reflection at a plane surface arises directly out of the quantum behavior of photons.

Every possible path from source to detector counts. But only in the middle are nearby paths closely similar in length, so that the ‘arrows’ associated with them are nearly in phase and thus ‘line up’. Further out, the phase changes rapidly as the path changes, so that the arrows from these paths ‘curl up’, giving a very small contribution to the final resultant arrow. Only the paths very close to the path prescribed by the law of reflection make an important contribution.

This explains Fermat’s principle of least time. The graph shows how the travel-time varies as the path changes. At the minimum the time does not vary as the path changes. So the phase associated with these paths does not change either. However, quantum thinking gives us something more. By thinking about *how much* the phase changes between

nearby paths we can estimate the limits to the description given by geometrical optics.

The traditional “wave-particle duality” story makes it seem as if wave and particle behavior are partial explanations of quantum behavior. Something more like the reverse is true. Particle behavior, in particular all of classical Newtonian mechanics *is explained by* quantum behavior (see Ogborn & Taylor 2005). Equally, the wave behavior of light *follows from* the quantum behavior of photons, in the limit of low photon energy and many photons. Quantum physics helps to explain why – and when – classical ideas work.

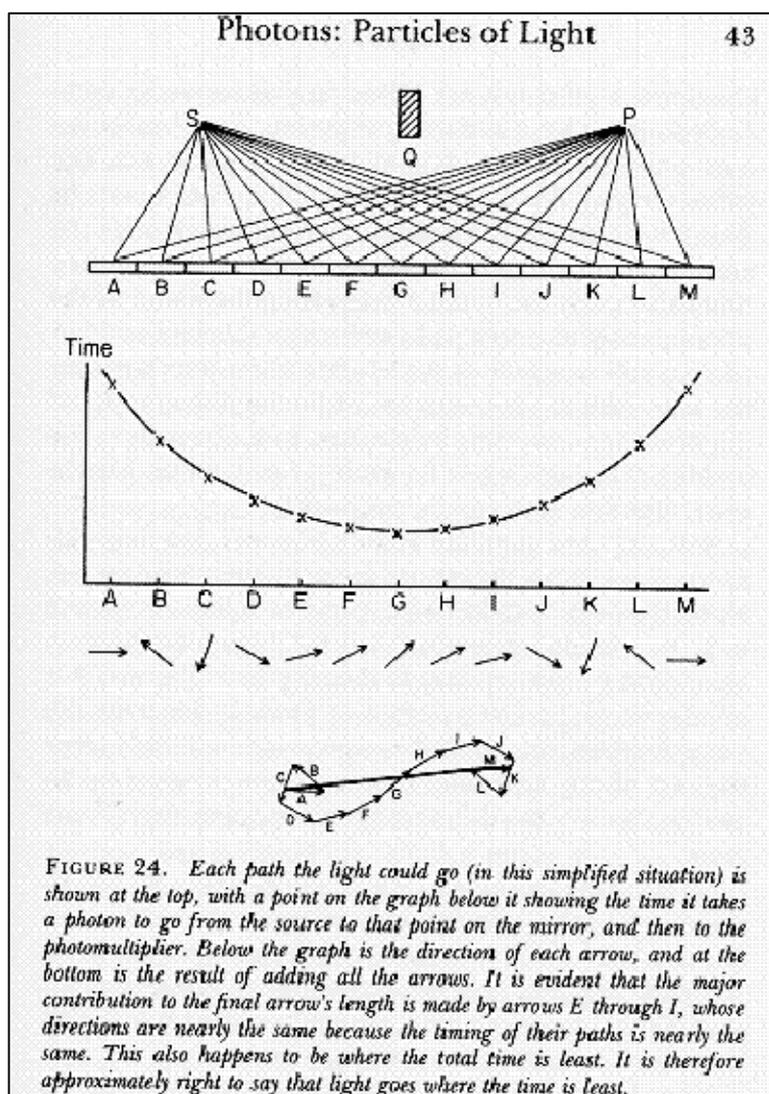


Figure 2 Reflection of photons at a plane mirror

### Step 6 Electrons do it too

The description of quantum behavior is appropriate not just for photons, but for all particles, including electrons. For a free (non-relativistic) electron, the rate of rotation of the quantum arrow is just  $K/h$ , where  $K$  is the kinetic energy. Demonstration apparatus available for school laboratories makes it straightforward to show electron diffraction. Even better is to see electrons arrive one by one, building up gradually into a

two-slit interference pattern. This has been achieved by a Hitachi team led by Akira Tonomura, who have produced a beautiful film clip of this most fundamental experiment (Tonomura et al 1999).

The rate of rotation of the phase of an electron is given by  $L/h$ , where  $L$  is the Lagrangian, and the total phase rotation is  $S/h$ , where  $S$  is the action along the path. We don't mention this to students in *Advancing Physics*, but we mention it here to show how the simple approach can be extended in later work.

### **Does it work?**

The only evaluation we have, so far, of the value of this approach is the experience of it being taught in about 25% of UK schools teaching physics at this level. The teachers have available to them an email network, to discuss whatever they please. Every year, when this topic is taught, there is a flurry of discussion, about what exactly the ideas mean and about how to respond to students' questions.

These discussions show that teachers new to the approach are understandably nervous, and need a good deal of re-assuring. It also shows that they, like their students, are prone to giving the ideas an over-concrete interpretation, particularly in wanting to associate a 'traveling phasor' with a 'traveling photon', rather than associating a phasor with a possible path.

Some ways of teaching the ideas lead very strongly to over-concrete interpretation. One popular idea is to push a rotating wheel along a number of paths and to note the total rotation for each path. This very effectively shows how, for example, the results of Figure 2 arise. But students inevitably want to know what role the wheel, and its diameter and speed, play in the theory.

However, it remains true that there is, in evaluation of the whole *Advancing Physics* course, no demand to remove or change this topic. Nor do students complain about the examination questions set on it. We can say, therefore, that this rather radical innovation has succeeded at least to the extent of having survived for six years so far, in a course taught on a national scale in schools of widely differing kinds. And at least a proportion of both teachers and students find it very interesting and thought-provoking.

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