The A to B of quantum physics

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The authors describe the way in which quantum physics is introduced in the new AS (Advanced Subsidiary) course *Advancing Physics*. It is based on the *sum over many paths* approach developed by Richard Feynman and described at an appropriate level in his book, from which the following quotation is drawn.

> What I am going to tell you about is what we teach our physics students in the third or fourth year of graduate school—and you think I'm going to explain it to you so that you can understand it? No, you're not going to be able to understand it. Why then am I going to bother you with all this? Why are you going to sit here all this time, when you won't be able to understand what I am going to say? It is my task to convince you *not* to turn away because you don't understand it. You see, my physics students don't understand it either. That is because *I* don't understand it. Nobody does.
>
> Richard Feynman [1]

In spite of—or because of—the above, 17 year-old physics students in some 350 schools in Britain will for the first time, in the academic year 2000/2001, be studying quantum physics using the approach Feynman used in his book *QED*. This is the Many Paths model of how light gets from A to B—and that electrons also follow the same strange routines. These students are following the new AS (Advanced Subsidiary) course developed by the UK Institute of Physics and called *Advancing Physics* [2].

So '*why bother (them) with all this?*' Up until now quantum physics as taught in secondary schools has been little more than a rather vague account of how Planck first thought of the quantum of energy a hundred years ago, with a closer look at Einstein's explanation of the photoelectric effect which introduced the idea that light was composed of quanta, eventually to be named photons [3]. We had wave–particle duality, which turned up as an intriguing idea, but there was no opportunity to use quantum ideas as a workable explanation of everyday processes such as how mirrors worked (the law of reflection) and why lenses can focus light. Being able to explain such things as 'the angle of incidence equals the angle of reflection' should alone justify teaching the Many Paths model, but an equally good if not better reason is that the whole thing is so *weird*. There seems to be an educational conspiracy to avoid telling the youth of today how really weird the world is. And almost all everyday events (in biology, chemistry and lots of physics) work just because this weirdness exists. Quantum electrodynamics (QED) is the most successfully accurate theory of physics so far discovered. Or invented. The Many Paths approach is intriguing and can give students immediate success in using the model. It gives a good foundation for further work, such as Feynman diagrams in particle physics, and the almost linear behaviour of high speed (high mass/energy) particles compared with say the behaviour of electrons at low speeds—electron diffraction for example.

Ed Taylor of MIT urges that introductory physics should begin with relativity and quantum physics using the Many Paths model. This can explain practically everything. Banish the Newtonian model of forces; $\boldsymbol{F} = m\boldsymbol{a}$ is redundant. More information can be found on Taylor's website [4].

Teaching Many Paths quantum physics

The approach used in *Advancing Physics* is best described as dynamically visual. Mathematics is kept to a necessary minimum but there is enough of it to make it physics and not just some kind of fairy story. Much of the maths comes in 'learning questions' and is at a sound pre-university level. The strong visual approach is via computer models, especially Modellus [5], which comes packed with the CD-ROM that contains most of the material required to follow the course [2]. The modelling is *dynamically visual*—students can see things happening as they happen, and *transparent*—the mathematics of the model is easy to access in the program. Students and teachers can change parameters themselves, as they see fit. All we can do here is give the briefest of outlines of what constitutes 10 hours of teaching time.

Starting to tell it

The teaching approach goes like this. A gamma photon is emitted from a radioactive source and detected by a counter that provides satisfying clicks. Close by, the clicks are almost continuous. Further away, the clicks occur randomly every second or so.

This is reality. Listen for quite a long time. Think about what is happening.

The students have just studied waves, and have been well rehearsed on superposition and even phasors. They are introduced to photons and that the energy of a photon is linked to a frequency: $E = hf$. This is easily done by measuring the potential differences at which LEDs of different colour are set glowing (see Lawerence [6]). They know or can easily be persuaded that some event inside a particular atom produces the gamma photon at point A. It gets to the GM tube at point B.

The gamma photons arrive randomly. How do they get from A to B?

We have no way of answering this question. *This fact is strongly emphasized to students.* All we can observe is what happens at A and what happens at B. We don't try to talk about wave–particle duality—this confuses the issue. When students studied waves they saw 'interference' effects, which are fairly easily explained on a wave model—but how can photons get into this act? Or, how can a 'wave' pack itself into a space small enough to trigger a GM tube? We don't know. We don't really care.

'Not wave behaviour, not particle behaviour, but quantum behaviour' [2, p 162]

Here come the weird bits.

Think of the f in hf as a frequency of rotation of something. Imagine it as a phasor that is linked (somehow) to the photon. Photons have not heard of Newton's laws and don't know that they should travel in a straight line from A to B. A photon explores all possible paths and then accepts what happens.

ALL paths? Surely you must be joking, Dr Feynman?

But let's see where it takes us. Students have to think about trip times and how many turns of the phasor will fit into a path from A to B. Any path. We know where the paths start and end up—at the source and at the detector. Simple pen and paper calculations give the phasor angle at the detector for any path we fancy. Modellus modelling makes this easier than pen and paper calculations, but it is worth doing it the slow way just to avoid the response 'you can make computers do anything'. We can make the Many Paths theory even more concrete: the most concrete is make a small 'trundle wheel' (figure 1)—or better, borrow a full sized one from a nearby primary school. A trundle wheel is used to measure distance: a rotation might mark out a metre of distance: from this we can find trip time, given a speed, and so the number of rotations, as we know the frequency. So a line drawn along a radius gives the direction of the phasor after a certain time spent exploring that path. What is the phasor angle after travelling a path? What is the sum of the phasors contributed by many paths?

Students then try this Many Paths model by condensing it to a simpler and familiar one: the two-slit interference pattern. Now there are just two paths.

The phasor approach shows that when photons go through the slits to *anywhere* on a screen there are places where phasors add up to give a large sum, and places where the phasors point in

Figure 1. A small trundle or photon wheel, made from Lego.

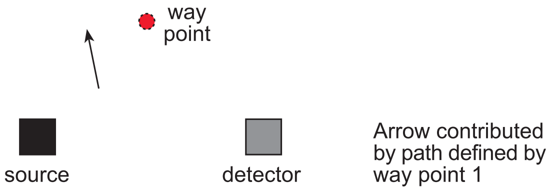

Figure 2. A rotating phasor on its way along a path.

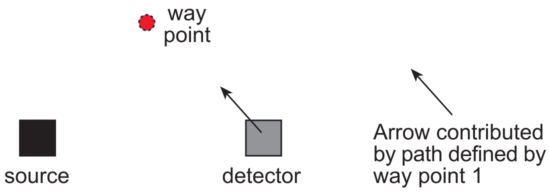

Figure 3. The phasor gets to the detector.

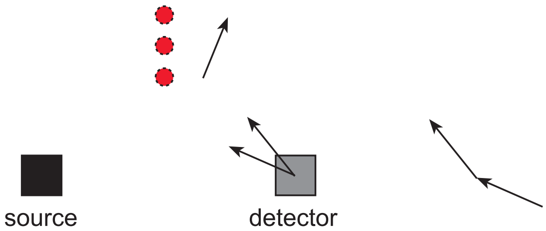

Figure 4. Sample paths that the phasor might take. Two phasors have arrived with the third on its way.

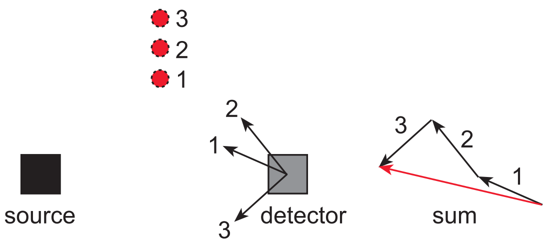

Figure 5. The sum of the three phasors in figure 4.

opposite directions and give a zero sum. The familiar slit pattern appears. But this time we haven't needed any *waves*.

Trundling wheels around playgrounds is slow—but definitely concrete. Software gives quicker results and is just as visual. The *Advancing Physics* course makes good use of the Modellus program, and here students can probe into a variety of situations in which moving phasors travel in many paths and meet at any point. All we 'see' is a rotating arrow. Figure 2 shows it on its way, via one simple, arbitrary path, to a detector. Figure 3 shows its direction at the detector. The software can show a variety of paths, and students can learn that the key factor is trip time. The program diagrams are of course in colour—so the figures in black and white here aren't as clear.

But our photon can explore an *infinity* of paths. We can show just three, as in figures 4 and 5 which show a stage on the way and then the final sum of the contributions from three paths. It might be mentioned here that summing over an infinite number of paths is what causes the mathematical difficulty of using the model. But at this stage that's somebody else's problem! What our simple software can show is that extreme paths contribute less than more direct paths, and that the extremes tend to cancel each other out anyway (figures 6, 7 and 8). So the outcome is that to expect light to travel in a straight line is reasonable even on this way-out model.

Mirrors

We can add three phasors from just three possible paths to see what happens when a photon is

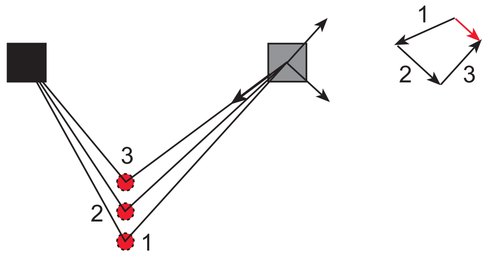

Figure 6. An extreme path.

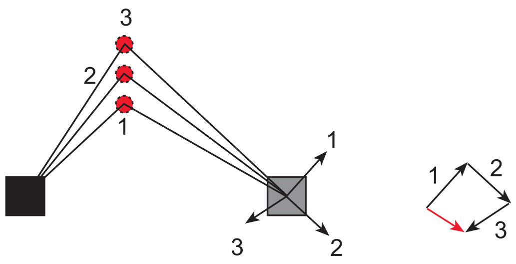

Figure 7. Another extreme path.

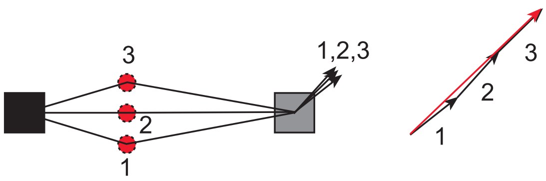

Figure 8. The paths that go more directly to the detector.

reflected by a plane mirror. Figures 9, 10 and 11 show this. In figure 9 the sum is fairly large but points in a radically different direction from the sum of figure 11. We might guess that when the photon is reflected from all over the mirror these phasor sums tend to cancel each other out. But we get a nice big sum for paths that get close to 'obeying' the law that angle of incidence equals angle of reflection (figure 10). More sophisticated software—or the more tedious trundle wheel—shows what happens when the photon is allowed many more than three paths to try out. It also works with curved mirrors.

Maybe there's something to this crazy model after all?

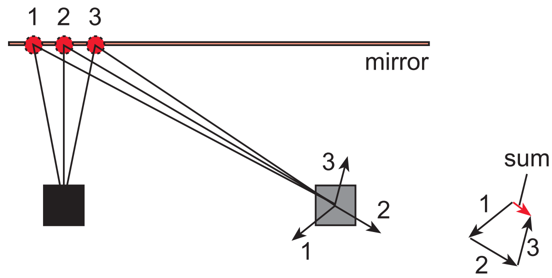

Figure 9. A sample path for a phasor being reflected by a plane mirror.

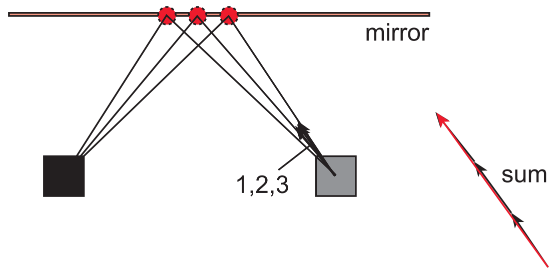

Figure 10. Another sample path for a phasor being reflected by a plane mirror.

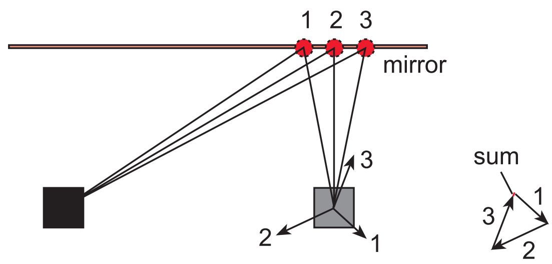

Figure 11. A third sample path for a phasor being reflected by a plane mirror.

Gratings

To cap this, take away bits of the mirror in a regular pattern: we have a reflection grating. Amazingly, the phasors add up to give what a grating should do! This is set as a question in which students calculate trip times for a particular setting and check whether the phasor sum is a maximum (figure 12).

Refraction and lenses

The idea of trip time gets perhaps more significant when photons travel through materials in which

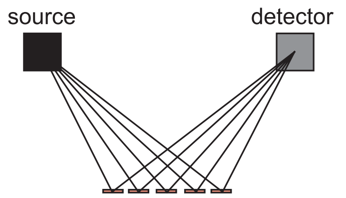

Figure 12. Part of a question about the effect of reflection from a mirror grating.

the speed of light is different. They meet the most useful work of the fashionable Pierre Fermat: The Principle of Least Action. Students can explore phasors and trip times for the many paths a photon might take in travelling from say air into glass. Best results come from shortest times and the paths give us $\sin i / \sin r$ equal to the ratio of light speeds. They can design a quantum lens that gives equal times (and so phasor spins) for photon paths and find that they get to a focus.

In the course students take 10 hours to cover the work—only a brief outline of which is presented here. Light and electron diffraction are covered, with 'real' experiments as well as computer modelling. All this is supported by questions of varying difficulty and readings. Most of this is on a CD-ROM, so that the textbook can be kept short and readable. Keen students can go on to consider the range of quantum behaviour, and link it to relativity and other modern (not yet 100 years old) ideas.

What do students get out of it all?

First, a taste of some really modern physics. It is only a taste—they explore a 'small corner of the quantum landscape in considerable detail, laying foundations and pointers for understanding quantum behaviour' as the *Teachers' Guide* puts it. But the main message is perhaps that a theory that goes so strongly against the grain of common sense can be so productive. Of course, it is this that might worry students most, especially those who look to science for some satisfyingly solid basis for explaining reality. Some chance in today's physics!

But the weirdness of it all does cause students some worries. A number of school teachers in the 25 'pilot' schools that began the course even as it was being developed have now taught Quantum Behaviour to real students and have gathered together some of the common student questions, and some attempts at real answers. As ever in a 'live' teaching situation the challenge is to keep the physics correct but also to make what is correct accessible. The top four student questions (probably in order) are given below, along with some general pointers about how teachers responded.

Frequently asked questions

(1) 'What do the photons *really* do?'

You are bound to be asked this. Just as if we were doing 'waves and particles' you'd be asked, 'What are they really—waves or particles?', to which the answer is 'neither'.

Students can clearly see that the photon cannot explore all the paths first and then decide on one it will choose. Equally clear is that we cannot imagine that over a number of photons all the paths are explored and information pooled because one photon, on its own, knows all about all paths.

The underlying student problem is that they think about the many paths diagrams in a very concrete way. The best approach is to make very clear that 'many paths' is a calculation device. What we know is that the photons leave and that they arrive. Between times if we *imagine* that the 'explore all paths' rule is what happens it allows us to calculate the outcome. It is the way that 'wave-like' calculations get into the story.

It is tempting to add that asking what 'really happens' is not allowed because we cannot know. But it's not a problem of ignorance: it's a problem of changing the experiment and so changing the result. If the experiment is set up to check on a given path, it becomes a different experiment, with new barriers and detectors. The fact is that any experiment gives the photon several possibilities. All possibilities have to be taken into account. The phasor sum is how possibilities combine in quantum behaviour. It's the rule of their game.

Students do not like this. Familiar with the idea that teachers hide the truth, they think 'we cannot know' means 'you cannot be told'. It is one of the really valuable lessons of this topic for students to gather that there are questions that cannot reasonably be answered because answering them changes the question being asked. An analogy that worked well was that of a teenage party at the parent's home. If the parent leaves the party and goes out they get to see the tidy house before and the mess afterwards. They cannot get to know how this happened. If they stay behind to see the mess be made, it will not be. The experiment changed! The difference is that the teenagers could remember how it happened, and tell, without changing what they did. But photons only tell by doing.

(2) 'But where are they really?'

This is a different version of the first question. The essential thing about quantum behaviour is that photons (and other particles) *are* localized in energy but *not* in space. Because their energy arrives in a lump at a given point in space and time, we think of 'the arrival of a particle'. Then, naturally, we ask how it got there. But the answer is not 'bit by bit along a certain path, like a bullet'. Energy got deposited at that place and time. It had several possibilities of getting there. All the possibilities have to be combined. And what makes this quantum behaviour is that each possibility (path) has a phase. So adding up isn't like ordinary adding up. More can mean less.

(3) 'Do the photons all travel at different speeds?'

This question is asked because students again look at the diagram and think in a very concrete way. The paths differ in length, so if they all arrive at the same time it looks as if the speed on the longer paths must be greater. Since they know that nothing can travel faster than light, this proves their physics teacher wrong and causes great excitement.

It's a good idea to accept the point that nothing can travel faster than light, and that therefore something that led you to that conclusion must be wrong. What is actually wrong is the assumption that the paths started out together. The possibilities that have to be added up (with phase) are ones for photons leaving the source a bit earlier or a bit later, so as to arrive on time.

With a few students, you might touch lightly on the further issue, that relativistically a photon takes zero proper time to go from any space–time event to any other.

(4) 'Does the amplitude of the phasor change as it travels further?'

Students know the inverse square law, or if not they know they can see a light less well if it is far away. So does the length of the phasor get less as it travels? The answer is yes. The further from the source you are, if you ask the question, 'will I find that photon here', the answer gets less. The calculation does that by making the amplitude smaller. It varies as $1/r$ so that the probability of arrival (amplitude squared) varies as $1/r^2$.

This objection can be dealt with, and to advantage:

(a) we ignore this length change because the distances do not differ by much,
(b) it helps explain why far-flung, long paths are less important and gives an answer to the question about which paths to concentrate on.

Summary

The quickest way for interested readers to find more detail about how a topic usually considered difficult and even esoteric can be made accessible to 17 year-olds will be for them to read chapters 6 (Wave behaviour) and 7 (Quantum behaviour) in the *Advancing Physics AS* Student's Book [2].

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