Chapter 7 Quantum Behaviour

Demonstration 20D Listening to photons arriving

You will need
pure gamma source
one or more Geiger–Müller tubes with counter with audio signal

Practical Advice
This is designed to be a memorable experience on which a theory of photons can be built.
Some 'pure' gamma sources based on Co-60 allow the associated beta rays out. These must be used with an aluminium filter about 3 mm thick to ensure that only the gamma rays are detected.
A possible extension is to ask students to find out how the number of photons arriving in a fixed period of time varies with the separation of the source and detector.

The focus here is on the behaviour of single photons. Recent experiments have shown that the fraction of photons which is found at a particular detector (something ordinary lab experiments can measure as the intensity of light) is an accurate map of the probability of detection of one photon at a particular detector. The same fraction arrive at different possible detectors as the intensity of the emitting source is reduced low enough for a single photon to be in the apparatus at once. Only by concentrating on moving from real waves interfering after travelling over real paths to possibilities of interfering after exploring virtual paths can we bring in the weird behaviour of the quantum in a convincing way.

Alternative Approaches
Photomultipliers are available which enable photons of lower frequencies to be listened to. You could show videos of photomultipliers detecting single photons –- thus showing the graininess of light. Photomultipliers themselves are devices with low quantum efficiency; the link between the clicks heard and the photons arriving is not direct.

Demonstration 240D Superposing electrons

You will need
electron diffraction tube
eht supply, 5 kV
4 mm leads
slab magnet
laser
transmission gratings, 300 and 500 lines / mm
white screen

Practical Advice
This experiment is crucial in suggesting that electrons can also be characterised as having a frequency and be well described by the many-paths formulation. This is an essential link as electrons are the exemplars for the whole of stuff. Two-slit fringes are being reported for molecules, and so the quantum description of matter is increasingly well established. The argument proceeds by analogy with the case for photons, which by now should be well established in students' minds.

Patterns made by multiple slits
This section is here to give you the chance to review the multiple slit patterns produced by photons, perhaps showing the software model as well, for which the more open-ended software OneParticle.ctb is more suitable. Show fringes made by different slit spacings, concentrating on the change in fringe spacing as the slit separation is altered, using the gratings of 300 lines / mm and 500 lines / mm (chosen in an approximate ratio of 1:1.7 to pre-empt the spacings in graphite), and on the need to characterise photons as having a frequency in order to describe these superposition phenomena. Perhaps then model the change in slit spacing on screen.

Multiple slits for electrons
Here you need to establish what will act as the slits and the reasons why we have made that choice. Short calculations may help. (Use

$$f = \frac{E}{h}$$

for photons and

$$f = \frac{E_K}{h}$$

for electrons.)
At 3 keV electrons have a frequency of 1016 Hz, compared with photons with a frequency of around 1014 Hz. Given the short length of tube, and the need to see the fringes as distinct, this suggests a rather fine grating.

Electrons through multiple slits
Set up the 'electron diffraction' tube in a darkened room. A simple circuit is shown here, you may need more complexity than this to produce optimal fringes – consult the detailed instructions provided by the manufacturer of the tube. Try in all cases to restrict the beam current and running time to reduce the damage to the graphite, caused by the arrival of the energetic electrons.
Do alter the kinetic energy of the electrons by varying the p.d.; rings should be visible over the range 3–5 kV. Point out and account for the decrease in size of the rings as the energy increases, by analogy with the increase in the frequency of light necessary to produce similar changes in the optical case. The increase in brightness can be accounted for by considering the number of electrons arriving per second and the energy of each electron.

You might like to draw on the Advancing Physics AS student's book, chapter 2 where ion beams get a mention, and, from more recent work, on arguments about intensity and number of photons arriving per second.
The magnet may be used to show that the whole pattern is deflected, the charged particles interacting with the magnetic field to produce this effect.

Worrying about the slits
This order, of placing the main ideas up front, and then coming back to the relationship between the fringe pattern and the gratings provided by the atomic array, may not be to everyone's taste. It is done this way to try and make sure that candidates of quite moderate abilities get to the main points. It is here that the level of detail of treatment may push this resource into being more suitable for A/B candidates.

We suggest that you show one 300 lines/mm grating and then rotate it. Then repeat for a 500 lines/mm grating. Then ask what happens when you cross these two, then again when you rotate this pattern. At this stage it may be useful to have a simple, but well anchored mount to facilitate this spinning. Then relate this pattern back to what is produced by electrons. It is probably important to emphasise that you are dealing with the first-order fringes from both gratings.
This may be omitted or edited out. But you may be able to convey the thought that the account developed for photons can be extended to electrons, and that a lot of ground can be covered by analogy – no fundamentally new techniques are involved in getting the calculations out. So the fundamental unity of quantum entities is shown: we have one formalism that accounts for a large range of different phenomena, even describing apparently quite different entities.

External References
Feynman R P 1964 Lectures in Physics Volume II (Addison–Wesley) p 19

Alternative Approaches
Videos of electron diffraction might be substituted for the real thing, if equipment demands cannot be met.

Presentation 40P:Microwave paths

You will need
microwave transmitter and detector
microwave beam splitter
microwave reflectors
multimeter to measure output from microwaves

Practical Advice
This is a quick look – just so that the students can keep in their mind's eye a clear picture of what we want the model we are about to construct to account for. It is a purely qualitative experiment – we are getting a feel for the phenomena. You might like to draw out the phasor description as a way of capturing wave behaviour without saying that there have to be physical waves.

You might extend it by having to hand a pair of 2.8 cm circumference trundle wheels, each marked with an arrow. Trundle the arrows along the paths to find the contributions of each path to the amplitude, and therefore the intensity. Practice to ensure that the set-up gives two arrows which are aligned when the intensity is a maximum and in opposition when the intensity is a minimum.

Presentation 150P:Reflection gratings: A selection

You will need
incandescent and fluorescent lamps
a CD-ROM for each member of the audience
a metal ruler
a laser
red, green and blue filters
small white screen
commercial reflection grating, if available

Practical Advice
You can make the point that reflection gratings involve no transmission, and therefore no absorption. This is particularly useful for frequencies that are absorbed by glass. A selection of different gratings will make the phenomenon to be accounted for more obvious.

Alternative Approaches
Draw on some of the work in chapter 6, where you may have looked at some reflection gratings.

Experiment 10E:Relating energy to frequency

You will need
multiple LED array
peering tube
power supply, 5 V
multimeter
five 4 mm leads

Practical Advice
We suggest setting up several competing research groups, and actively encouraging students to form a consensus about the relationship between frequency and energy. An appropriate degree of collaboration gets the correct answer; inappropriate degrees yield a work of fiction or no consensus. Thus can physics progress.

Students will know about the existence of an LED from previous work on electricity and will know that it conducts in one direction only. Thus electrons, simply introduced as what moves when electricity is conducted, can be presented as meeting an electrical barrier when the LED is reverse biased and falling down that barrier when forward biased. This simple model of the action of an LED is enough for this purpose. Connecting this electrical model to an energetic model requires the notion of potential difference to be reviewed as being likely to be the sensible way of determining the height of the barrier and the energy as being the potential difference times the charge on the electron.

Analogies with the energy released in falling down a hill can reinforce this idea. So as to make sure that none of the electrical energy is dissipated (actually as phonons) we need to insist that we require the smallest p.d. across the photodiode. This energy, plotted against the frequency of emitted light (taken from the manufacturer's specifications), can then be used.

Experience shows that the measurements made by the students may not be so accurate, and that encouragement to settle on a simple pattern, together with the consensual approach suggested above and the ability to make several measurements before deciding on the accurate answer, will be necessary. A class using a graph-plotting package may make this review and interaction more likely. Students should easily establish $E = h f$. A consensus on the value of h should give a value that is far from embarrassing.

Sample results:

LED colour	Wavelength / nm	Frequency / 10^{14} Hz	Striking p.d. / V	Energy / aJ	h / 10^{-34} J s
Blue	470	6.38	2.38	0.381	6.0
Green	563	5.33	1.69	0.270	5.1
Yellow	585	5.12	1.63	0.261	5.1
Orange	620	4.83	1.48	0.237	4.9
Red	650	4.62	1.47	0.235	5.1

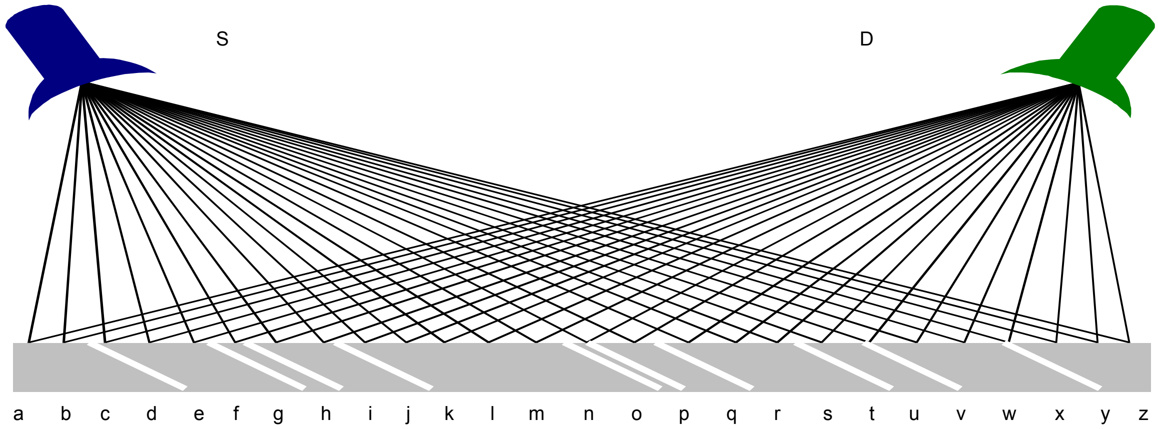
Technician's note: You can find instructions on how to construct the array of LEDs in the Teacher and Technicians Information.

Alternative Approaches
To establish the connection between the energy associated with each click – or the arrival of each photon – we suggest measuring the energy required to release one photon of light in a light-emitting diode. This has the advantage that we can cheaply try out several frequencies and rapidly obtain a picture of how energy varies with frequency. It is, of course, not the only technique for establishing a link between frequency and energy. You may substitute others. The photoelectric effect has been used for this for many years, as has appeal to the evidence of spectra.

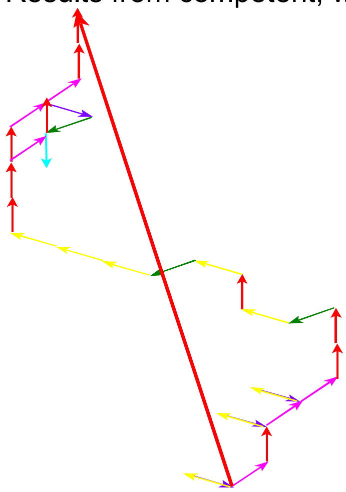
Experiment 80E:Calculating for a mirror on the bench

You will need
pencil, ruler, vector sheet
or
hexagonal grid printed from File 60I 'A hexagonal grid'
red or blue photon wheel
many paths for a mirror sheet printed from File 50I 'Paths for a mirror'

Practical Advice
This simple exercise takes around 20 minutes. Some care is needed to produce sound results, but these are possible.
Some care is needed in deciding how to characterise a mirror by the choice of waypoints, and some discussion will need to precede trundling wheels across patterns on paper. You need to build up gently towards a diagram such as this one:



Here we provide a concrete route into the use of many-paths calculations. Many students will benefit from the slowing down that this exercise will bring, and from the way in which the patterns build up. That these do so from pure geometry emphasises the simplicity of the theory. However, not too long should be spent on analysis. The pattern made by the arrows is important, but students are likely to meet it again, and the mirror should be studied using software as well.
Results from competent, well-briefed students may well look like this:



Alternative Approaches
You could do the whole thing at a much larger scale, on a whiteboard as a demonstration, in the playground with trundle wheels, or jump straight to software.