Bringing Young to life

In my mind — and I suppose this comes from some book I read in my youth — I see protons as tiny blue spheres. Neutrons are brown spheres of the same size, electrons smaller and yellow. Photons are also yellow, although blurred out a bit. My automatic imagery is completely in the spirit of pre-quantum physics, taking the ‘particle’ terminology quite literally. I expect many physicists carry around similar intuitive images, even if they know they cannot be taken seriously.

After all, Young’s famous two-slit experiment reveals the limitations of the particle concept for real quanta. With both slits open, the quanta within a coherent beam sample both possible paths to a screen behind. Despite always impacting the screen at a precise point, they build up an interference pattern over time. Close one slit, and the interference is destroyed. No simple scheme of particles following precise trajectories can account for both outcomes (although non-classical schemes, such as the one developed by David Bohm, show that the notion of precise trajectories can be preserved).

The strange outcome of this experiment is a staple of undergraduate physics education. Oddly enough, however, real experiments showing these effects don’t ordinarily play a part in that education. You can’t easily just set up a laser, shine it on a pair of slits, and see single photons registering the statistical interference pattern on a photographic plate, despite many textbook discussions to that effect. At least you couldn’t do this until now. Physicists Reuben Aspden, Miles Padgett and Gabriel Spalding have devised a clever scheme to do the experiment in the undergraduate lab using commercially available equipment, including a laser and a CCD array detector (preprint at http://arxiv.org/abs/1602.05987; 2016). Seeing the experiment in simple terms probably won’t change the images in anyone’s head of what quanta really are, but it’s a beautiful example of essential quantum behaviour brought to life.

In the historical development of quantum theory, the first experiments revealing the wave character of massive particles relied on crystal diffraction, rather than close analogies to the two-slit set-up. Famously, Clinton Davisson and Lester Germer, while working at Bell Labs in 1927, observed the diffraction of slow-moving electrons from the surface of a nickel crystal. For light itself, the two-slit experiment was first performed with feeble light as early as 1909 by British physicist Geoffrey Taylor, who observed an interference pattern from single-photon impacts by running an experiment over a period of six months. Even today, a similar experiment can’t be done using ordinary photographic cameras due to inherent optical noise — especially during camera read out — that ends up swamping the signal, making it impossible to observe the single photon impacts as they build up the statistical interference pattern.

Real experiments showing these effects don’t ordinarily play a part in undergraduate education.

What Aspden and colleagues have done is to reduce the noise through careful timing. Their idea is to keep the camera turned off most of the time during the experiment, turning it on only for brief intervals to include the moment of photon arrival. That sounds tricky, but is in fact fairly easy — conceptually, at least — by using entangled photons. Two correlated photons can be created at one moment, with one being directed toward the two-slit apparatus, and the second going elsewhere. This second photon can then be used as herald, its detection at a known distance away being used to trigger a switch to turn the camera on, briefly, and just in time for the first photon’s arrival.

As the authors describe, this can be done using parametric down-conversion in beta barium borate crystals. The nonlinear optical properties of such crystals lead to the absorption of a single photon, and the subsequent simultaneous emission of two photons of half the energy. In their set-up, a pump laser enters the crystal and its photons generate a stream of pairs of entangled photons. A beamsplitter ensures that, from each pair, one travels forward toward the two-slit apparatus and the CCD camera, and the other — the herald photon — goes elsewhere. A heralding detector stands ready to absorb this photon and send a trigger signal to the camera.

Aspden and colleagues fashioned two slits 100 µm wide and separated centre-to-centre by 500 µm, and illuminated the slits with down-converted photons at 710 nm. As a heralding detector, they used a single photon avalanche diode, and, for the camera, an Andor iStar Gen III intensified CCD. As a minor point, they added an optical delay line to the camera arm to compensate for the time taken by the triggering operation. Except perhaps for the camera, all the relevant technology, they note, is already available in undergraduate labs at hundreds of institutions. This is the equivalent of laboratory microscopes or pendulums but for basic quantum theory.

The results of the experiment are, of course, just as expected — although presented with remarkable clarity and simplicity in a set-up easily mastered by students. With a coherent beam, transmission through the two slits generates a series of crisp interference fringes. After a few dozen or even a few hundred photons, no clear pattern is yet evident. But the fringes become very clear after a few thousand single photon detections. (For videos of the results see http://go.nature.com/woaz1w).

The authors also show how the set-up can be used to display some of the peculiar consequences of photon entanglement. You wouldn’t normally expect a beam of photons sent directly to an imaging screen — and not encountering any slits at all — to show an interference pattern. But what if those photons were entangled with others that do encounter some slits? The two down-converted photons are correlated not only in time but also in space. Hence, it’s possible to take the two-slit set-up and place it into the arm of the herald, rather than the camera. In this configuration, Aspden and colleagues show that the photon beam again produces an interference pattern even though, in this case, none of the photons ever interact with the two slits. The authors refer to this as ghost interference, as it reflects Einstein’s reference to the “spooky action at a distance” involved in entanglement.

Again, none of this is really ‘new’ physics. It’s old physics beautifully displayed. And soon to be enjoyed, I expect, by students around the world. ❐

MARK BUCHANAN