

DORIS. Part of DORIS opened up for maintenance, showing some of the powerful magnets used to focus the beams of electrons and positrons. The three magnets in the foreground are half of a set of six magnets which encircle the particle beam pipe (the blocked-off white circle at the top of the photograph) when the machine is running. Behind these three magnets, we can see half of a set of four magnets which does a similar job. There are many sets of each kind of magnet in DORIS.

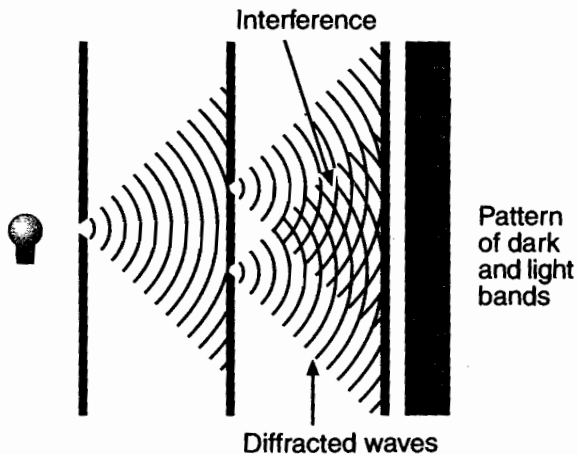
The famous cosmological redshift of galaxies, associated with the expansion of the Universe, is not, however, due to the Doppler effect, because it is caused by space itself stretching, not by galaxies moving through space.

DORIS Acronym for DOuble RInG Storage facility, built at the DESY laboratory in the mid-1970s. DORIS was built with two rings one on top of the other, so that two beams of electrons, or one beam of electrons and one of positrons, could be accelerated at the same time, one in each ring, and then made to collide with one another. It operated at an energy of 7 GeV and helped to establish the existence of the tau particle.

double-slit experiment The experiment which, in the words of Richard Feynman, encapsulates 'the central mystery' of quantum mechanics. It is 'a phenomenon which is impossible, *absolutely* impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the *only* mystery ... the basic peculiarities of all quantum mechanics' (*Lectures on Physics*, Vol. III).

Most people first encounter the experiment with two holes, as Feynman used to refer to it, in the classic demonstration of the wave nature of light. Early in the 19th century, Thomas Young used such an experiment to demonstrate the wave nature of light, and it is still sometimes referred to as 'Young's double-slit experiment'. In this version of the experiment, light is shone on to a screen (maybe a simple sheet of

double-slit experiment

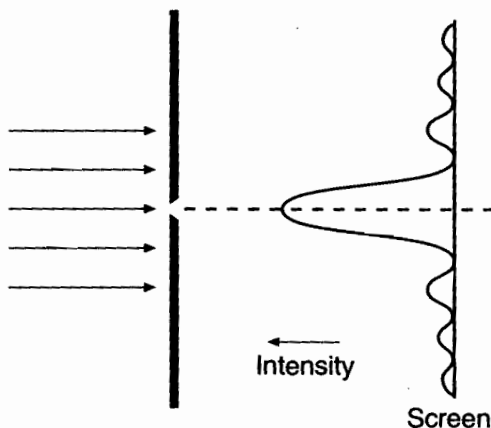


Double-slit experiment 1. When a beam of pure light passes through the experiment with two holes, the diffracted waves interfere to produce a characteristic pattern of light and shade.

cardboard) which has a small hole (or a narrow slit) cut in it. After passing through this hole, the light arrives at a second screen which has two holes in it. Light spreading out from the two holes in the second screen finally falls on a blank wall or screen, where it makes a pattern of light and shade.

The pattern of light and shade made in this way is called an interference pattern, and it is explained as a result of light spreading out from the two holes (as a result of diffraction) in a series of overlapping waves. In some places, the two sets of waves march in step and add together to make a bright patch of light; in other places, the two sets of waves move out of step and cancel one another, leaving darkness. You can see exactly the same kind of interference pattern in the ripples on a pond if you drop two stones in to it at the same time (or if you wiggle a couple of fingers around in your bath water).

This is not the way a stream of particles hurtling through the experiment would behave. If you stood behind a wall in which there were two holes, and hurled rocks through the holes, you would end up with two piles of rocks, one behind each hole.



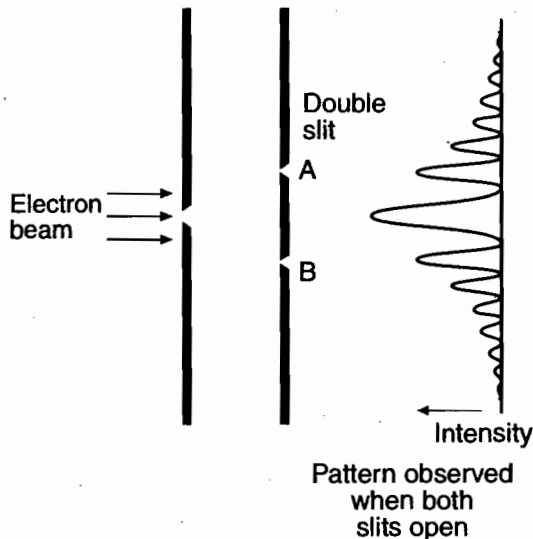
Double-slit experiment 2. If you threw rocks through a hole in a wall, you would expect them to pile up with most rocks right behind the hole. If electrons are particles, this is the kind of pattern you would get building up on a detector screen if you fired them through a small hole one at a time.

There would be no interference. So if light were a stream of particles, you would expect to find just two bright patches on the detector screen, one behind each hole, not an interference pattern. One of the most distinctive features of the interference pattern is that the brightest patch of light is not behind either of the two holes, but exactly halfway between them, behind the obscuring screen. There is a very low intensity of light just either side of this peak, and then a succession of lesser peaks, separated by lows, repeating alternately as we move out along the detector screen.

The brightness of a patch of light is measured in terms of intensity, which is equal to the square of the amplitude of the wave at that point; in the interference pattern, for two waves whose amplitudes are represented by H and J , the intensity at any point is not given by $(H^2 + J^2)$, but by $(H + J)^2$, which works out as $(H^2 + J^2 + 2HJ)$. It is the extra term, $2HJ$, which is the contribution due to interference from the two waves, and, making allowance for the fact that the H s and J s can be negative or positive, it precisely explains the highs and lows in the interference pattern. If both waves have the same amplitude, as they have in the classic Young's slit experiment, the brightest patch of light in the interference pattern is four times brighter than either wave would produce alone (because $H = J$, and $HJ = H^2 = J^2$), and at the other extreme the term $-2HJ$ (which is equal to $-2H^2$ or to $-2J^2$) exactly cancels out the other two terms to leave utter blackness. It all works beautifully as long as we are dealing with waves.

Curiously, though, exactly the equivalent of Young's experiment can be carried out using a beam of electrons, which we are used to thinking of as particles, and it produces exactly the same results. Electrons fired through a double-slit experiment produce an interference pattern on the detector screen (in this case, a screen rather like a TV screen, where the arrival of each electron makes a single point of light). Even this is not yet the 'central mystery', but notice what we have just said. Electrons are fired through the experiment and make an interference pattern, so they must be travelling as waves. But the arrival of each electron at one particular place on the

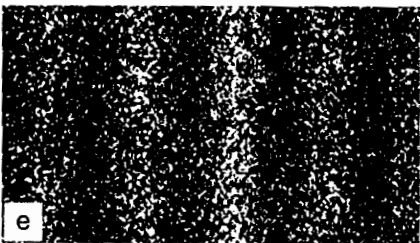
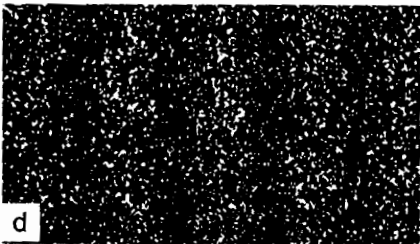
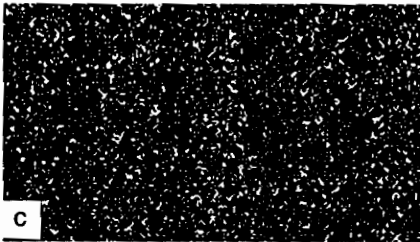
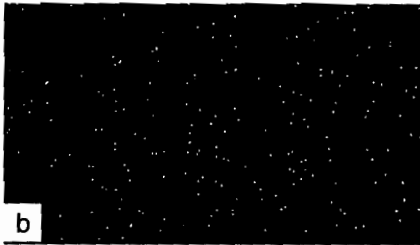
Double-slit experiment 3. If you fire an electron beam through the experiment with two holes, you get an interference pattern, as if the electrons were waves. The brightest part of the pattern is midway between the two holes. You do not get the pattern you would expect by adding up the two patterns corresponding to particles going through each of the two holes independently, which would give you two bright peaks, one behind each hole.



double-slit experiment

screen makes a single spot of light. So they are arriving as particles! Quantum entities travel like waves but arrive as particles. And although light is 'proved' by Young's experiment to be a wave, there is other evidence that light also can be regarded as a stream of particles (see *photon*).

This would be worrying enough if we were only dealing with beams of electrons (or photons) containing large numbers of particles. In that case, we might hope to explain the interference pattern as some sort of statistical effect. But the central



When a Japanese team at the Hitachi Research Laboratories, headed by Akira Tonomura, fired electrons one at a time through the experiment with two holes, the classic interference pattern associated with waves gradually built up on a detector screen (like a TV screen) on the other side of the experiment. Each electron made a single spot on the screen, proving that it was a particle; but the interference pattern proves that electrons are waves.

(a) The pattern after 10 electrons had arrived.

(b) The pattern after 100 electrons had passed through the experiment.

(c) The pattern after 3000 electrons had arrived.

(d) The pattern for 20,000 electrons.

(e) The pattern for 70,000 electrons.

Remember that each electron passed through the experiment on its own; the screen 'remembers' each spot of light as the pattern builds up.

mystery of quantum mechanics is revealed in all its glory when single quantum entities (either photons or electrons) are fired *one at a time* through the experiment, and the pattern they make on the detector screen is allowed to build up gradually.

We stress that this really has been done, both for photons and for electrons, with the pattern they make being allowed to build up on a TV-type screen (or on photographic film) as the spots made by each arriving photon or electron accumulate. Now, *single* particles are travelling one at a time through the experiment, and each makes a single spot on the screen. You might think that each particle must go through only one or the other of the two holes. But as more and more spots build up on the screen, the pattern that emerges is the classic interference pattern for waves passing through both holes at once. The quantum entities not only seem to be able to pass through both holes at once, but to have an awareness of past and future, so that each can 'choose' to make its own contribution to the interference pattern, in just the right place to build the pattern up, without destroying it.

There's more. If you think this is fishy, and set up a detector to tell you which hole each particle is going through, all of this mysterious behaviour disappears. Now, you do indeed see each particle (photon or electron) going through just one hole, and you get two blobs of light on the detector screen, without interference. The quantum entities seem to know when you are watching them, and adjust their behaviour accordingly (again, we emphasize that this version of the experiment really has been carried out). Each single quantum entity seems to know about the whole experimental set-up, including when and where the observer is choosing to monitor it, and about the past and future of the experiment (see also *delayed choice experiment*). And this doesn't just apply to electrons and photons, although they are relatively easy to work with and have been studied most intensively. It applies to all quantum 'particles', and similar experiments (with similar results) have been carried out with neutrons, protons and even whole atoms.

Hold on to these ideas, and remember them when you are reading about the other mysteries of the quantum world. As Feynman summed the situation up, in his book *The Character of Physical Law*, 'any other situation in quantum mechanics, it turns out, can always be explained by saying, "You remember the case of the experiment with two holes? It's the same thing."' See also *probability wave*, *Copenhagen interpretation*, *transactional interpretation*.

doublet A closely spaced pair of lines in a spectrum – for example, the two lines that together make up the bright yellow sodium D line. They are explained by electron spin, which allows two electrons with opposite spin states (up or down) to share almost the same energy level in an atom.

down One of the six *flavours* that distinguish different types of *quark*.

dressed charge The charge of a quantum entity, such as an electron, measured at long range. This can differ from the *bare charge* of the entity, which it exhibits in short-range interactions, because of the way the entity is 'dressed' in a cloud of virtual particles.

dressed mass The effective mass of a quantum entity, such as an electron, measured at long range. This can differ from the *bare mass* of the entity, which it exhibits in very short-range interactions, because of the way the entity is 'dressed' in a cloud of virtual particles.



Drift chamber. A drift chamber, dubbed WA1, at CERN. This particular example is 20 metres long and weighs 1500 tonnes.

drift chamber The electronic equivalent of a *bubble chamber*, in which parallel wires are strung out in a chamber full of gas, across which an electric field is applied. When a charged particle passes through the gas, it produces an ionized trail which drifts in the electric field and triggers the detectors linked to the wires. Developed in the 1970s by Georges Charpak at CERN.

Dubna Location of a major particle physics research laboratory (JINR) in Russia, 100 km north of Moscow. Home of a 10 GeV proton synchrotron accelerator.

Dyson, Freeman John (1923–) British-born American physicist, best known for his clarification of the theory of quantum electrodynamics in the late 1940s, when he showed that the theories of Richard Feynman, Julian Schwinger and Sin-Itiro Tomonaga were equivalent to one another.

Dyson was born on 15 December 1923 in Crowthorne. His father later became the director of the Royal College of Music. He studied at Winchester College and moved on, in 1941, to Cambridge, where he made original contributions to mathematical theory while an undergraduate. In 1943 Dyson left Cambridge and carried out wartime work at the headquarters of RAF Bomber Command, where he realized that the way the bombing effort was being carried out was a needless waste of airmen's lives, but was unable to persuade his superiors to change their approach to the war. After the war, he worked for a time at Imperial College in London as a demonstrator (a very junior teaching post) in mathematics, while writing a th