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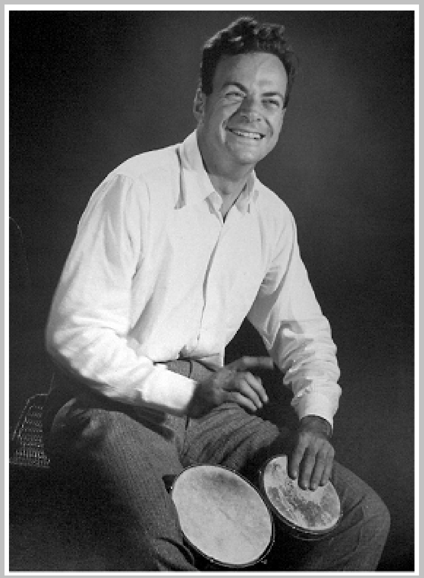
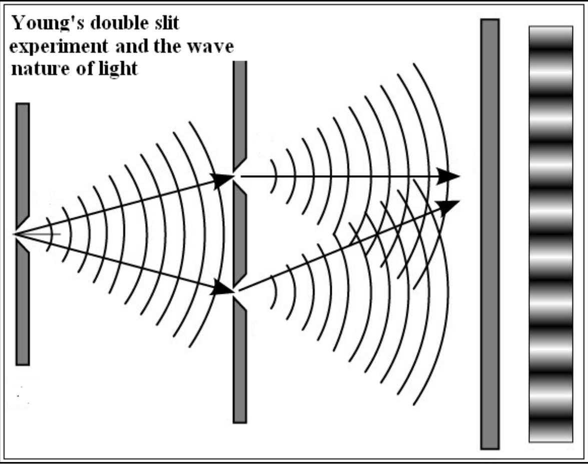
Thought experiment done for real

Feynman's imaginary, teaching example has been made to work in the lab, says S.Ananthanarayanan.

Richard P Feynman is the Nobel laureate, legendary physics expositor, who created more committed physicists, professional or amateur, perhaps, than his great contribution to physics itself. He is renowned for his maverick, informal, but direct teaching methods and is celebrated for the 3 volume, "Feynman Lectures on Physics', the record of the undergraduate course that he taught at MIT in the 1960s. A celebrated 'thought experiment' that he used to introduce quantum mechanics, an experiment so called because it could happen only in the mind, has been practically carried out, report **Roger Bach, Damian Pope, Sy-Hwang Liou and Herman Batelaan,** at the University of Nebraska-Lincoln, USA and at Waterloo, Ontario, Canada, in ***The New Journal of Physics.***



Particles and waves



Light was first conceived as consisting of a shower of particles, or ***corpuscles***, as early scientists, including Sir Isaac Newton, called them. Later studies showed this was not true and at the scale of very small distances, 'light did not throw sharp shadows', but behaved like a wave. A celebrated experiment with light waves was to pass a beam through a pair of slits, set close together, and on to a screen at some distance. Light that came straight along the centre-line traveled the same distance from either slit, and shone brightly on the screen. But at distances off the centre, the light wave from one slit could be a half wavelength further off than light from the other slit, and the 'crest' of one wave would clash with the 'trough' of the other, to use an analogy of waves in water, and there would be a dark band. A little further away, the path difference would be a whole wavelength and the waves again create a bright image. And in this way, there would be a pattern of ***fringes***, on the screen, rather than a single bright line. It was this experiment, among other evidence, that established light as consisting of waves, later shown to be electromagnetic waves.

And then, in the early 20th century, while studying the way a warm object radiated heat at different frequencies, it became necessary again to correct course, as light, for all its qualities of a wave, was found to consist ***lumps***, or ***quanta***, which is to say, ***particles,*** called ***photons***. That energy was carried by light only in discrete packets, the higher the energy of the packet, the higher the frequency, was soon firmly established, and proved by the ***photo-electric effect***, where the electrical effects of light packets were found to depend on their frequency.

In the meantime, another conjecture was that where waves could show particle behaviour, particles should act like waves too, the greater their momentum the greater the frequency of the wave. This was also experimentally realized, in experiments showing that a stream of electrons, which were quintessential particles, could form patterns when scattered, just like X Rays passing through a piece of crystal. These were ways of behaviour of nature that were non-intuitive and with no analogy in experience.

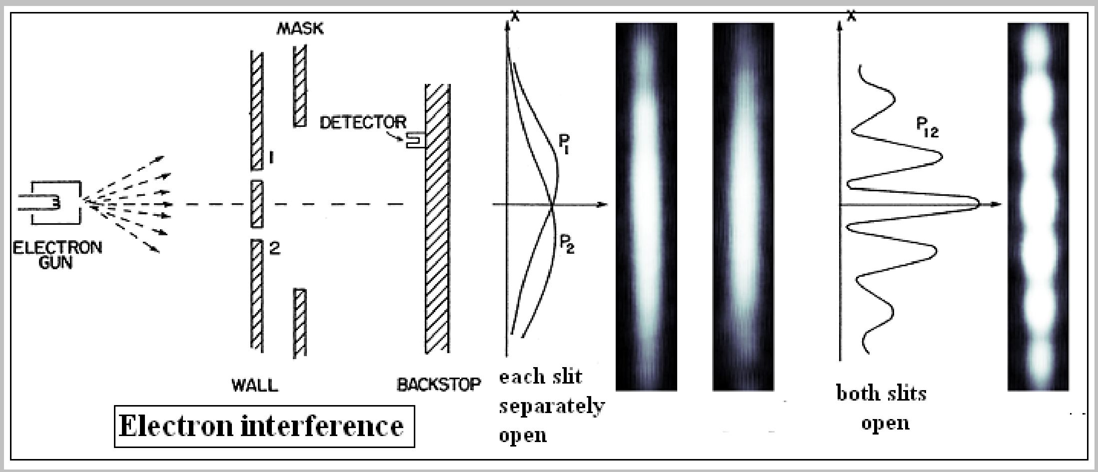
The concept of energy states in finite steps, transitions between which led to emission of light of given frequencies, was successful in explaining the structure of the atom and much behaviour of matter at the very small scale. An elegant mathematical system, based on established classical laws of motion and incorporating the particle properties of waves and vice versa, was developed and became incredibly successful in working with matter at the atomic and subatomic level. The concept of exact location or exact energy of a particle had to be given up, for a certain fuzziness of position and inherent uncertainty of all measurement. A state of a system was seen as endowed with simultaneous potential for all possible values of its parameters, some values being more probable, in the event of measurement, the probability changing, when the dimensions of the system were large, into the certainty that we find in the familiar world. But at the elementary level, it was an unreal, particle-wave scepter that throws the dice which decides the outcome of interactions.

Feynman lectures

To introduce the fascinating but unfamiliar world of how systems actually worked, before they averaged out to the familiar laws of motion, Feynman created his classic example of the two slit experiment conducted with electrons, in place of light. When conducted with ordinary light, a pair of slits a millimeter apart can create fringes that can be made out with a microscope at a distance of about a meter. But the effective wavelength of particles with the mass of electrons is so many thousands of times smaller than that of light, that Feynam's experiment would need slits placed really close together, as also a detector at a very fine scale to make out any fringes. Feynman hence made it clear that the experiment he proposed was in the mind only, and was meant to explain the way matter behaved, as learnt during the first half of the 20th century.

The experiment was first to shine ordinary light on the pair of slits and observe what happened when either slit was open and again when both were open. When any one slit was open, light shone on the screen intensely when directly before the slit, and falling off, in a bell shaped curve, as one moved away. Normally, hence, when both slits were open, the illumination should have been the addition of the effect of the slits by themselves. But as we know, this does not happen, because of the wave nature of light and the effect is called ***interference***.

Now, Feynman proposes the experiment using not light but a beam of electrons. Again, with only one of the two slits open, the distribution at the screen is like in the case of light. But when we consider the case with both slits open, we are now dealing with electrons, each of which is separate particle and would move only through one or the other of the two slits. In fact, if the source of electrons is made feeble enough, we can ensure that only one electron reaches the screen at any time, and as that electron has come through one of the two slits, the result of all the electrons should be no different from just the addition of the effect of each slit by itself. And yet, this is not what happens, the result is a pattern of fringes, just like in the case of light!



Electron interference

Feynman proposes that we could check up what was happening by keeping a watch on each electron to trace which slit it passed through. Now, if the distribution of electrons reaching the screen is plotted, with the path of each electron identified, again, the pattern is like the sum of the patterns of each slit by itself, there is no interference pattern. But stop watching the electrons, and the fringes reappear!

There is no intuitive explanation for what is going on. It would appear that the effect of each electron on the screen is the sum of the ***probabilities*** of the electron going through either slit. This is in keeping with the idea of uncertainty of the location of the electron, at the scale of the experiment. When working with probabilities, with both slits open, there is interference outside the centre-line and hence the pattern of fringes. But when there is a measurement of which path the electron took, which limits the uncertainty of position, there is only one path and the interference of the probability of the other path vanishes. But stop making measurements, and interference comes back.

This imaginary experiment demonstrates many mysterious aspects of the very small world. The quantum computer, for instance, uses components that can be in a large number of states at the same time. For example the spin, up or down, of a pair of particles can be, both up, both down or up and down. Two such pairs can interact in 3x3=9 ways.

A quantum computer would act in a manner analogous to the slits in the experiment when the electrons are not watched – and would evaluate all possibilities simultaneously. But such a computer is a delicate system and the slightest disturbance would throw each system into one of its possible states and only one combination would be evaluated. This would amount to the electron being ‘watched’, typically by shining a light and a photon getting scattered by the electron.

> *"There was a time when the newspapers said that only twelve men understood the theory of relativity. I do not believe there ever was such a time. There might have been a time when only one man did, because he was the only guy who caught on, before he wrote his paper. But after people read the paper a lot of people understood the theory of relativity in some way or other, certainly more than twelve. On the other hand, I think I can safely say that nobody understands quantum mechanics." R P Feynman, in the course of his lecture on the double slit experiment.*

Two slit in practice

The achievement of the Canada-USA scientists is to use modern technology to actually demonstrate Feynman’s thought experiment. The scientists used a 100 nanometer thin sheet of silicon nitride coated with a 2 nanometer layer of gold. With a precise focused beam of ionized atoms, they cut slits that were 62 nanometers wide and 272 nanometers, or 272 millionths of a millimeter apart. The mask, used to block either of the slits, was a huge 4.5 thousandths of a millimeter wide and the arrangement was mounted on a sliding frame to perform the experiment. The image was magnified using a lens that consisted of electric fields and the detector was a state of the art, ***charge coupled device*** camera.

The results of the experiment, when the mask was used and when it wasn’t, were just as Feynman described. Not that there was any doubt, but here was modern nano-fabrication techniques giving shape to an image of unparalleled simplicity and technical rigour, that looks at electron diffraction, “which has in it the heart of quantum mechanics” (to quote R P Feynman), with the insight that could come from none other than the master!