What is light?: Is light a wave or a particle - or both? The central mystery of quantum physics is coming under scrutiny as researchers try to measure the wave properties of a single photon

- 02 November 1991
- From New Scientist Print Edition..

- DIPANKAR HOME and JOHN GRIBBIN

Three centuries ago, Isaac Newton argued that light behaves like a stream of tiny particles travelling in straight lines, and is reflected from mirrors in the same way that a ball bounces off a surface. But early in the 19th century, Thomas Young, in England, and the Frenchman Augustin Fresnel established an alternative theory, that light is a wave: it can bend around sharp edges and spread out through two narrow slits in a screen to produce an interference pattern, in the same way that ripples on a pond interfere with one another. The wave theory of light became the 'classical' description used in optics. Later, in the first quarter of the 20th century, experiments revealed that light, or electromagnetic radiation, seemed to possess both properties typical of waves and properties typical of particles. The same applied to matter which is made of particles such as electrons, which also behave as waves.

This duality is one of the key puzzles of quantum mechanics, the most successful theory we have of the way matter and radiation behave at the atomic and subatomic levels. How can something be both a particle and a wave at the same time? Common sense, based on our experiences in the macro world, says that this is impossible. But quantum mechanics requires that in the micro world, light, electrons and other entities can behave as either wave or particle, depending on the experimental arrangement.

The 'either/or' has been the escape clause enabling physicists to preserve their sanity. In any one experiment, the standard interpretation of quantum mechanics tells us, light - or an electron - should behave either as a particle or as a wave. But, according to that conventional wisdom, established by Niels Bohr and his school in Copenhagen in the late 1920s and 1930s, it cannot exhibit both wave and particle properties simultaneously. In the late 1980s, however, a new generation of experiments, so subtle that they involve observations of single photons, began moves to block off the escape clause.

It seems that the interplay between wave and particle aspects of light in certain experiments is more intricate than Bohr envisaged. This provides further impetus to the effort initiated by several theorists, including the late John Bell, to contemplate something that has been almost unthinkable for 60 years - a fundamental revision of physicists' interpretation of what quantum mechanics means.

The enigma of wave-particle duality can be demonstrated by imagining a standard interference experiment in which light passes through two holes in a screen to fall onto a second screen (see Figure 1). This is Young's double-slit experiment, as performed by every schoolchild studying physics to prove that light is a wave. In that school experiment the light waves interfere like water waves passing a similar obstruction to form a characteristic pattern on the second screen.

The conventional wisdom also sees light as propagating in packets of energy called photons, which may be regarded as particles of light. Our imaginary experiment differs from that in the school laboratory because our hypothetical apparatus allows only one photon at a time to be emitted by the light source. These photons then pass through the holes in the intervening screen, and are detected by a counter of some kind that can be moved about on the surface of the second screen. With a steady emission of photons from the source, the rate at which photons arrive at the detector will depend on its position on the surface of the second screen. More photons will arrive each second on some parts of the screen than on others.

By moving the detector about, we can build up a picture of the pattern made by the photons. Quantum mechanics predicts that this will be the standard interference pattern, just as if each photon has somehow gone through both holes in the intervening screen, and interfered with itself before deciding where to go next.

The pattern builds up strictly in accordance with the statistical probabilities required to make interference fringes, even though the arrival of each photon at the detector is unambiguously localised, like a particle. And, clearly, a localised particle can only go through one or other of the two holes in the intervening screen.

So what happens if we set up an experiment to monitor which hole each photon goes through? This is easily done by placing detectors at each of the holes, connected to a coincidence counter which lets us know if both detectors are triggered simultaneously. In our idealised experiment, with just one photon at a time being emitted by the source, common sense tells us that the coincidence counter will never be triggered. For once quantum mechanics agrees. It predicts that we will find that each photon passes through only one hole. But we will also find that in these circumstances there is no interference pattern built up on the second screen, simply two patches of light, one behind each hole. It seems that if light is allowed to behave like a wave then it will; but if it is constrained to act like a particle, then it does.

The American physicist Richard Feynman stressed that this wave-particle duality contains the central mystery of quantum mechanics. Indeed, he went further, saying that 'in reality it contains the only 'mystery' of the theory'.

According to the standard interpretation of quantum mechanics, which is known as the Copenhagen interpretation, the problem of the incompatible descriptions of light obtained by analysing what is going on in the two versions of the experiment is evaded by saying that the experiments are mutually exclusive and cannot be performed at the same time. From this viewpoint, it is possible to observe either the wave properties or the particle properties of light, but not both simultaneously. This is a central feature of what Bohr called the principle of complementarity.

The complementarity principle is not without its critics, however, and has recently been the subject of intense scrutiny from diverse viewpoints. But before we discuss the subtle questions raised by those critics, we want to look at the plausibility of experiments such as the one we have just described. Are these merely imaginary 'thought' experiments, in which case the basis for those subtle arguments about complementarity is speculative? Or are there real experiments that correspond to this kind of experimental setup, in which case the complementarity debate has a much sharper focus?

A key issue is just how we should regard photons. The notion of light particles stems from Albert Einstein's explanation, in the early years of this century, of the photoelectric effect. This is the name given to the emission of electrons by metals when light falls on them; it is used in all light meters and many cameras to measure the intensity of light. Einstein showed that each emitted electron received the same amount of energy from a monochromatic light source, whatever its intensity. His explanation was that light consists of a beam of quanta, or photons, all of which had the same energy for a particular wavelength of light. This was the work for which Einstein received the Nobel Prize for Physics in 1921.

Although the photoelectric effect is held up as the archetypal proof of the particle nature of light, there is an alternative explanation. Several researchers, starting with David Bohm in 1952, have shown that the photoelectric effect could be accounted for by considering light as an electromagnetic field interacting with, say, a metal surface composed of discrete atoms. The observed characteristics of electron emission then result because the detector is made of atoms with discrete energy levels . So it is arguable that the photoelectric effect does not establish unambiguously the reality of photons.

There is no problem about proving the wave nature of light. As long ago as 1909 Geoffrey Taylor showed that extremely weak sources emitting highly attenuated pulses of light still produce wave-like behaviour. But what would be the most convincing demonstration of the particle character of light? Studies in quantum optics have shown that all the common sources of light such as thermal lamps, discharge lamps and even lasers emit light in states (the so-called classical or semiclassical states) where there is no possibility of observing particle-like behaviour. In order to observe particle-like behaviour we need sources emitting what are known as single-photon states of light. All the classic two-slit experiments have relied on conventional light sources. There are now plans, however, to conduct new two-slit experiments using single photons.

One of the simplest experiments of this kind involves single-photon states of light impinging on a beam splitter. This is a mirror that allows half of the light falling on it to pass through while half is reflected - easy enough for a wave, but any individual photon should be either reflected or trans-mitted, not both. In other words, for single-photon states, the standard rules of quantum theory predict perfect anticorrelation for detection on the two sides of the beam splitter: every time the detector on one side is triggered, the detector on the other side is not (see Figure 2).

On the other hand, any description of the propagation of light involving classical waves always predicts that there will be some coincidences between the two detectors when a pulse of light falls on the beam splitter. Alain Aspect and Philippe Grangier of the University of Paris have calculated the minimum number of coincidences expected on the classical wave picture. They showed that the probability of coincidence (Pc) should be greater or equal to the probability of reflection (Pr) multiplied by the probability of transmission (Pt). This inequality can be expressed as Pc >= Pr Pt. On the other hand, quantum optics predicts Pc = Pr Pt for laser sources and Pc = 2Pr Pt for thermal sources; for single photon sources Pc = 0. If the inequality is found to be unambiguously violated then the classical wave picture is clearly falsified.

In their new experiment, Aspect and Grangier first used a conventional source of light (a pulsed photodiode). This was strongly attenuated so that individual light pulses were well separated and the average energy per pulse was much less than that of one photon; in fact, it was about one-hundredth of the amount of energy carried by a single photon. This seemingly nonsensical possibility is allowed because, in quantum-mechanical terms, the classical or semiclassical states of light do not correspond to definite photon numbers. Rather, they are 'superpositions' involving quantum averages of states with definite photon numbers. The average number of photons can be much less than one if many of the states that are averaged over actually contain zero photons.

The striking feature was that even under this apparently 'quantum' condition the light pulses arriving at the beam splitter continued to behave as classical waves and the inequality was never violated. This confirmed that usual sources emit light in states that display a wave-like behaviour even when the beams are of very weak intensity. The next step was to work with a source producing genuine single-photon states.

Familiar sources of light, such as discharge lamps, emit light by the excitation of many atoms. Because they are excited at random times and the number of atoms emitting light varies, the statistical properties of the emitted light are identical with those expected from the wave picture even if the light is made up of photons. In the same way, ripples on a pond are, strictly speaking, a statistical effect resulting from the motion of very large numbers of tiny particles. But it is possible to isolate the emission from a single atom; this was first convincingly achieved in 1977 by Jeff Kimble, Mario Dagenais and Leonard Mandel at the Rochester Institute of Technology in New York State. Similar techniques are now being applied to beam-splitter experiments.

In these experiments, the source of light is composed of calcium atoms that are excited from their lowest energy or ground state to a higher state. When the atom falls back into its ground state it radiates in rapid succession two photons with different wavelengths. This is because there is an intermediate state between the excited and the ground state. After the first photon is emitted, the atom is left in an intermediate state which has a lifetime of 4.7 nanoseconds.

To catch a single photon the excited calcium atom is monitored with a detector that responds to the first-level photon and opens a 'gate' to allow light to pass for a short time. The duration for which the gate stays open is matched to the density of excited calcium atoms so that there is a high probability that any light getting through the gate will indeed be the second-level photon. In this way, researchers obtain a close approximation to the ideal situation of working with genuine single photons.

With such a source of single-photon pulses, Aspect and Grangier claimed to have observed a clear-cut violation of the inequality deduced from the classical wave picture. They concluded that their beam-splitter experiment showed genuine particle behaviour of photons. But could they observe interference - a wave phenomenon - with the same light source?

To test this they used the same source and the same beam splitter, but the detectors on either side of the beam splitter were removed and the two beams were recombined in a second beam splitter (see Figure 3). This is very much like a rerun of the experiment with two holes. They found that the detection rates measured on either side of the second beam splitter showed interference effects that depended on the difference in path length along the two possible routes of the individual photons.

This is a striking example of how the deep-seated conceptual issues of quantum mechanics, which used to be the preserve of philosophers, are becoming amenable to experimental studies, thanks to spectacular developments in technology. Of course, the interpretation of such an experiment is a delicate issue: perhaps inevitably, there are still different points of view on what it all means.

For example, Trevor Marshall of the University of Manchester and Emilio Santos of the University of Santander in Spain have claimed that the observed rate of coincidences between detections in the two routes in Aspect's beam-splitter experiment can be explained in terms of the wave picture by introducing the notion of 'stochasticity'. This means that the amount of incident light reflected or transmitted by a beam splitter fluctuates from event to event, with the specified portion that is reflected or transmitted being only an average. Logically this is possible, but in the absence of any physical understanding of how stochasticity arises it may seem artificial and forced. Nevertheless, Lucien Hardy of the University of Durham has pointed out that this type of stochastic behaviour would also alter details of the interference effect in the second version of the experiment, and this might be used to test the idea. The important point is that such debates are no longer confined to the domain of metaphysics, but can be settled by experiment.

A variant on the beam-splitter experiment has recently been proposed by one of us (Home) and two colleagues, Partha Ghose of the S. N. Bose Institute for Basic Sciences in Calcutta and Girish Agarwal of the University of Hyderabad. The idea is to replace the beam splitter by a two-prism arrangement - a combination of two prisms placed opposite each other, separated by a small air gap (see Figure 4). When the gap between the prisms is larger than the wavelength of a single photon arriving at the interface, then the photon should be totally internally reflected in the first prism. But if the gap is less than one wavelength, quantum optics predicts that the single-photon states will either be totally internally reflected or will tunnel through the gap and emerge from the second prism. In fact, you could identify each photon registered in one of the two detectors (one placed to register photons emerging from the second prism and the other to detect those reflected from the first prism) and label it according to the route it has followed.

Tunnelling is exclusively a wave phenomenon; it could never happen for a classical particle. Working with single-photon states, tunnelling can still occur, but any individual photon must either tunnel or be reflected, so there should be perfect anticoincidence between the two detectors. No one has done this experiment yet, but it raises the intriguing prospect of observing particle behaviour (anticoincidence) and wave behaviour (tunnelling) in the same apparatus and literally with the very same photons. Such experiments would help us to sharpen our conceptual understanding of the wave-particle duality, Feynman's 'central mystery', and critically re-evaluate Bohr's cherished notion of complementarity.

The notion of mutual exclusiveness of classical concepts such as wave and particle, or position and momentum is the key element in complementarity. We have concentrated on wave-particle duality, but if complementarity fails in one case then it fails as an overall description of the quantum world. There are different ways of looking at what complementarity 'really means'. The usual approach is to treat it pragmatically. Physicists exploit either the wave or the particle model of light as the situation demands. But this is simply learning to live with the dilemma, not resolving it.

The alternative to complementarity comes from the 'realist' school of quantum theorists, Louis de Broglie and David Bohm, who argued that the contradictions can be resolved by probing deeper into the nature of reality underlying quantum phenomena. Physicists taking this viewpoint say that a quantum entity such as an electron is actually a localised particle, but that its behaviour is guided by a physically real field satisfying the basic quantum mechanical equations. John Bell, the quantum theorist, also remarked that this type of wave-particle synthesis 'seems to me so natural and simple . . . that it is a great mystery to me that it was so generally ignored'.

In recent years, a growing number of physicists have been developing different versions of the 'realist' picture of the nature of light. These possibilities will be investigated by experiments as the technology we have described here improves. But three centuries after Newton, we have to admit that we still cannot answer the question 'what is light?' As yet there is still no answer to the basic question: is light 'really' a wave, a combination of wave and particle, or something entirely different which cannot be comprehended except as an abstract mathematical description? As Einstein remarked in 1951, four years before his death, in a letter to M. Besso: 'All these fifty years of conscious brooding have brought me no nearer to the answer to the question 'what are light quanta?' Nowadays every Tom, Dick and Harry thinks he knows it, but he is mistaken.'

Dipankar Home works at the Bose Institute in Calcutta.

Further reading: The Feynman Lectures on Physics, volume III, Richard Feynman, Addison Wesley, 1965; John Gribbin, In Search of Schrodinger's Cat, Black Swan, 1984; J. S. Bell, Speakable and Unspeakable in Quantum Mechanics, Cambridge University Press, 1987; F. Selleri, Quantum Paradoxes and Physical Reality, Kluwer, 1990.

* * *

WHO NEEDS PHOTONS?

A particularly simplified model to explain the photoelectric effect using the idea of a classical electromagnetic field starts from the description of an atom in its ground state (un-ionised) which has access to a continuum of excited ionised states, but with a finite energy gap (E) between the ground state (Eg) and the excited states.

The interaction between the incident light and the atom can be modelled by the interaction between an incident, classical electric field and the atomic electric dipole moment. Following the standard rules of quantum mechanics, one can calculate the transition rate of the atom from the ground state to the excited states, consistently treating the electric field as a classical field with an amplitude A and oscillating with an angular frequency.

This transition rate turns out to contain all the features of the photoelectric effect. For example, the threshold energy of the photoelectric emission is related to the existence of the finite energy gap E.

The probability of detection is proportional to the intensity A2. The final energy of the atom is found to be Eg + where is Planck's constant (h) divided by 2. So the binding energy of the electron in the excited state is Eg + E and the kinetic energy of the ejected electron is - E - and all without invoking photons at all.

From issue 1793 of New Scientist magazine, 02 November 1991, page 30