IMPACT OF THE PHOTON

The experimental discovery of photons at the turn of the century showed finally that electromagnetic theory had failed. Waves or particles, or both or neither? "Double-think" became the order of the day, a required belief; but are we sure that the last word has been said about this logical conflict?

BY W. A. SCOTT MURRAY
B.Sc, Ph.D.

The impression given by writers of scientific textbooks is that everything in classical physics was tidy, or about to become tidy, until 1899 when Max Planck came along and spoiled it with his quantum hypothesis. We have seen that this popular history misrepresents the truth. Electromagnetic theory, which formed one of the three structural pillars of classical physics, had already been placed in extreme philosophical difficulty by the Michelson-Morley result – no physical ether, therefore no electromagnetic waves. The whole of fundamental thinking at this time was based on electromagnetics; even the ordinary mechanical mass of an ordinary physical particle, such as an electron, was considered to be "electromagnetic mass', attributable to the inertia of its electromagnetic field, so that this field could be thought of as replacing the electron's material mass and even, by some physicists, to *be* the electron itself. In these circumstances the suggestion that anything could be seriously wrong with electromagnetic theory just didn't bear thinking about. One simply had to soldier on, hoping that some solution would turn up to relieve the anxiety.

However, the inconvenient absence of a physical ether was not the only evidence of failure of the electromagnetic theory. Serious difficulty was also encountered in describing the processes of radiation and absorption of light. The trouble in the radiation process was resolved by Planck by means of the revolutionary hypothesis which finally shattered the complacency of his times: *the radiation of energy in the form of light by a material substance is not a continuous process.* Individual mechanical oscillators in the material – atoms or molecules – radiate individual quanta of light energy. In the case of the absorption of light there is additional evidence of a discontinuous process: the photoelectric effect, which had similarly defied analysis by classical theory, was readily explained by Einstein on the basis of Planck's new hypothesis. The only possible interpretation of this high-quality experimental evidence is that the whole of an individual package of light energy or quantum must always interact, at any rate in the first instance, with one individual microsystem in the photocell surface. The light energy seems to be localized in space.

There was on the face of it, and in retrospect, nothing very surprising about this deduction. The essential granularity of matter on the microphysical scale, atoms and molecules, had been recognized for a hundred years. These newly discovered quantum interactions suggested that light energy also is packaged granularly into "photons" which behave as discrete corpuscles or particles, as Newton believed. The reason for the fuss was that the concept of a light beam as a shower of photons was in direct conflict with electromagnetic theory, because the latter, being a theory of linear force fields, depended absolutely on the *continuity* and extension in space of the quantities it was dealing with. By contrast, the concept of a particle or photon epitomizes discontinuity. Electro-magnetic theory *was bound to fail* when confronted with this discontinuity – and fail it did.

To those physicists who had believed the beautiful electromagnetic theory to be universally true and who had accordingly espoused it with a quasi-religious fervour, and likewise to those who so revere it by tradition today, its overthrow in the face of the quantum evidence, undeniable though that evidence might be, was simply not to be tolerated. Human feelings at levels deeper than mere reason were involved in this conflict. If mysticism was to regain its lost foothold in science, here was fertile ground.

Naturally, various attempts were made to compromise. The most hopeful of these led to the concept of the wave-packet. In certain circumstances, chief among which is that the physical medium in which they travel must be dispersive – a technical term – a group of water waves will propagate together across a pond and will remain concentrated together in the form of a package. The energy represented by the wave system travels at the speed of the group, which is not the same as the speed of the individual waves. (The mathematics of this situation is quite elegant). Hence it was suggested that the quantum, the particle-like concentration of light energy which was deduced from the experiments, might be merely a wave-packet of dispersive electromagnetic waves. That was the view which Planck himself took of the matter and maintained with some vehemence.

The trouble with this idea – it is distressing but noteworthy how often one is forced to say "the trouble with this idea . . ." – the main trouble with this idea is that although a suitable wave-packet could remain stable indefinitely in the longitudinal direction, no configuration of linear (Maxwell) waves can be devised which would prevent a wave packet from dissipating *across* the direction of the propagation. Now a beam of light will dissipate laterally, exactly like a wave system, but the individual quanta of which it seems to be composed *do not dissipate.* The unimpeachable experimental evidence for this is that the intensity of light decreases with distance from its source (the beam becomes more widely spread out), but the energy of its individual photoelectric impacts (its colour) does not change with distance. For this reason, Einstein, the radical, disagreed with Planck and came to regard the quanta as photons, essentially indivisible whilst in transit and therefore of the nature of particles. The wave-packet concept was a non-starter, disproved by the evidence, but it is still offered to physics students today as though it were valid and relevant.

In the end, and in my view prematurely, a thoroughly unsatisfactory compromise based on mysticism seems to have won the day. Modern physics as now taught accepts the doctrine of duality, which says that light radiation (sunlight, radio waves and x-rays) consist of both waves and particles at the same time. Whether its wave-like or particle-like properties predominate will depend on the details of the particular experimental set-up. If I use a diffraction grating I shall see waves; if I use a photocell I shall see photons; if I follow a diffraction grating by a photocell I shall see both forms of light within the confines of the same experiment. It matters not that waves (as in electromagnetic theory) and photons (quantum theory) are mutually-exclusive concepts, each of which specifically denies the validity of the other. If I am to make a successful career in physics I must learn to ignore that logical conflict and get on with the remainder of my job as though the conflict did not exist.

The duality doctrine can be fully accepted only by a person who is able and willing to "double-think" in the George Orwell sense. For every other professional physicist the choice is either to live with the doctrine – reluctantly and with resignation, no doubt, knowing it to be unsound – or to try to do something about it: but what? The problem of the true nature of light radiation is recognized to be one of surpassing difficulty which may "for fundamental reasons" actually be insoluble. There even exists a powerful school of thought which believes that matters of this fundamental kind are intrinsically beyond the power of the human mind to understand, so that it would be wrong to expend time, effort, or public money on attempting to understand them. It is asserted by this school that modern quantum theory is "complete" (Niels Bohr), and since that ultimate theory offers no solution to the problem there *can be* no solution to it (von Neumann).

Believe me about this, please, for I am telling you the truth: that view is the accepted dogma of today's scientific establishment. It follows from the arguments of the so-called Copenhagen School during the 1930's, while the body of doctrine now known as the quantum mechanics was under development. That doctrine is no more sacrosanct than was electromagnetic theory, and it rests on very much less secure experimental foundations (see later). It categorizes the fundamental nature of light as a *non-problem* for physics, about which it would be improper to ask further questions. Its bland assertion that there "can be" no further progress toward understanding in this and similar areas constitutes the ultimate in defeatism. For myself, I do not accept it.

Now if I declare that I do not accept one of the currently established doctrines of physics, in this case the doctrine of duality, the onus is on me to provide an alternative that I and others may find more acceptable. This I cannot yet do; nor, I expect, will anyone now be found who is able to review and revise the whole of modern physics single-handed. What I can do is invite those of my colleagues who are interested and not too busy to take a fresh look with me at the duality paradox, and I can start the ball rolling by mentioning a few neglected facts that may help us on our way.

My first hopeful factor is this. It is not waves as such, but *electromagnetic theory* – a field theory – which is inconsistent with the existence of discrete, particulate photons. When we are dealing with the most familiar waves of all, sound-waves in air, we do not normally have to remember that the true picture is one of interactions on the microphysical scale between myriads of individual air molecules. Rather than seek to follow and account in detail for the motion of each and every air molecule, which would be an impossible task anyway, it is sufficient for almost all purposes to consider their average behaviour. We speak in terms of local mean pressure and local mean velocity, and using these terms we can describe the propagation of sound as "waves" of pressure and velocity moving through the gas. Now the point to be made is that the *mathematics* of this description of sound is concerned with waves in a continuous medium, yet we know from other experiments that the true nature of a gas is not that of a continuous medium but of discontinuous, discrete molecules. The sound waves are real waves, however; their crests and troughs represent concentrations of air molecules which move progressively and systematically through the gas; and those density changes remain wavelike even though the gas is not mathematically continuous. It is not the waves but the mathematical theory of the waves which is inconsistent with the molecular nature of the gas. Clearly the theory is *an approximate description*, valid only in limited circumstances.

In electromagnetic theory the roles corresponding to local gas pressure and velocity are played roughly, but not exactly, by Maxwell's field potentials and displacement currents. It is these mathematical artefacts of the field theory, demanding as they do continuity in an ether medium, which are in conflict with the quantum evidence for the granularity of light. Light waves might very well consist of periodic variations in the density of photons as they travel in bunches through empty space at velocity c. If this should be so the infamous dualistic doctrine would be shown up for the mystical nonsense that I, for one, believe it to be. And the conflict would no longer lie between the concepts of light waves and photons, no longer incompatible, but between the electromagnetic theory and the experimental evidence. That theory also would be no more than a limited analogy at best.

It would be quite wrong to pretend to any originality for this idea, which Sir Karl Popper has quoted as representing Einstein's view. The concept that light waves consist of bunches or concentrations of photons is so obvious that one has to ask why it has not been generally accepted in place of the duality doctrine. Part of the answer would seem to lie in a general belief that it has been disproved experimentally. I am now going to argue that despite popular belief the concept has not in fact been disproved, but that it deserves at least one further, careful examination.

Typical of the experiments in question is one involving the interference of light, which is so readily accounted for on a "pure-waves" theory. I cannot do better than quote from an article written by Professor Frisch, of Cambridge, in 1969:

> "But what happens to the *photons* in an interferometer? At first it was thought that interference occurred when two or more photons came together; but that was disproved when G. I. Taylor (1909) showed that interference fringes were formed just the same whether the light was strong or whether it was so weak that hardly ever two photons passed through the apparatus together. It follows that single photons can exhibit interference, that 'a photon can interfere with itself'. It would seem that something does travel along both paths in the interferometer even when only one photon is admitted; but what is it?
> "Such questions were discussed a good deal when photons were new, and similar questions arose out of wave-particle duality of 'material' particles such as electrons. Some agreement has been reached on the way they should be answered, but the agreement is not unequivocal, and many of us are not sure what to tell our students . . ."

Summary

The crisis in electromagnetic theory threatened the whole of 19th-century physics. The threat became extreme when evidence of the radiation law (Planck, 1899) and the photoelectric effect (Einstein, 1905) showed that on these issues at least the electromagnetic theory had already definitely failed. The concept of the wave-packet, proposed by way of compromise, proved to be untenable. Eventually the mystical doctrine of the simultaneous waveparticle duality of light radiation came to be accepted, perhaps with resignation, together with the parallel doctrine that no fundamental understanding of this duality could ever be achieved. The onus was thereby placed on those who do not accept such negative doctrines to provide more acceptable alternatives to them. One such alternative, attributable originally to Einstein, proposes that light "waves" may consist of periodic variations of photon density. It is generally believed nowadays that this concept was disproved long ago, but careful investigation suggests that this is not so. Modern technology provides the possibility of a series of more rigorous experiments which could decide this very fundamental question once and for all. The main difficulty with such experiments is the practical one of obtaining financial support, because the concept underlying them is in conflict with the established dogma of modern physics.

The G. I. Taylor referred to was a research student at Cambridge under Sir J. J. Thomson. In his experiment he set up and recorded interference fringes on photographic plates, and the essence of his result was that no change could be discerned in these fringes whether the light was of visible intensity or so weak that to record the patterns required an exposure lasting three months. In the latter, extreme, case it could be calculated that if photons existed they must on average be separated by 30cm, which was appreciably more than the dimensions of the apparatus. Hence on average only one photon was present at any one time; yet the interference fringes still appeared in the photographs.

I submit that a point may have been missed by Taylor, by Thomson, by later experimenters who may have repeated the test, and by all who have accepted this result as evidence that "a photon can interfere with itself".* Everybody seems to have assumed that natural photons are evenly distributed in space, and that their density will be diluted evenly when the light intensity is attenuated toward zero. That is the assumption on which the deduction rests in this and similar experiments, but I suggest that it may be a false assumption. I propose in its place the idea that photons generated naturally – by a black-body radiator for instance, or in a discharge tube – are generated not singly but in very large bunches. Then in the experiments of Taylor and others the photons, although infrequent in an average sense, would nevertheless have continued to manoeuvre in bunches. There never was a time when the apparatus contained only a single photon, and interference *between* photons, rather than within individual photons, remained the order of the day.

Can I substantiate this proposal? Yes, I believe I can. In 1917 Einstein published a derivation of Planck's quantum law which later became the theoretical basis of the modern laser, and is therefore quite likely to be true. In this derivation he deduced the existence of two kinds of radiating mechanism which he denoted A and B. The A-type was spontaneous emission, self-triggering, while the B-type was stimulated emission, in which an atom or molecule previously primed with energy was triggered by the arrival of a photon already in flight. Following from Einstein's proposal, in the radiation of visible light the occurrence of B-type (stimulated) emission may be up to a thousand million times more frequent than A-type (spontaneous) emission.

We may interpret this result in non-mystical, mechanical terms. It should mean that photons are normally radiated in a cascade process: that is, in bunches. Each bunch would consist of up to a thousand million stimulated emissions, triggered ultimately from the one photon that is emitted spontaneously to initiate the cascade. This would represent the biggest snowball effect known to man – going on all the time on our doorstep, without our having noticed it. (I have coined the phrase *semi-laser action* to describe this process; the emission of *wave trains* can be explained in a natural way by interpreting Planck's $E=h\nu$ as $E=h/\tau$, where τ is the delay-time for emission of a photon of energy E).

If this argument should prove to be even moderately near to the truth (and I would gladly settle for a bunch of a million photons rather than a thousand million, not being greedy), we would have good reasons for repeating the Taylor experiment with modern photon-counting equipment. At sufficiently low light levels the interference phenomenon should simply fade away, like sound in sufficiently rarefied air. It would not be an expensive experiment by modern standards but it would be *very* fundamental and I say, worth the trouble of performing it. (I would have done it myself at home if I could have found the necessary £50,000 for equipment!) The key to the test would be to ensure and demonstrate that the photons were constrained to pass through the apparatus truly one-at-a-time. To forestall misinterpretation in these mystical and doctrinally-loaded surroundings would call for the greatest care. Also we may note that there is nothing "impossible" about this experiment, except that according to the Copenhagen dogma the question it asks is an improper question – just a bit too fundamental for comfort.

If it were thus to be shown that, contrary to current doctrine, the interference of light is a group phenomenon not evidenced by individual photons, we would be well on the way to a resolution of the duality paradox. A series of options in physics would be re-opened, which for fifty years have been dismissed as old-fashioned, "unphysical", or merely "unrealistic" – epithets which, in context, carry a pleasing irony. In the meantime we may examine some of the consequences to which a positive experimental result might lead. WW

*The wording of Taylor's report makes it clear that his boss, Thomson, did not hold with the new-fangled quantum ideas. Having obtained a result in accord with classical theory he was not disposed to investigate the issue further . . .

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