Take a Photon . . .

O. R. FRISCH
Cavendish Laboratory, Cambridge, UK

When light falls on an ideal half-silvered mirror half of it goes through, the other half is reflected. This is readily understood if we consider light as waves: we get a transmitted and a reflected wave, each having half the original intensity. But light is also a stream of photons, each carrying the energy amount hν. The frequency ν of the waves is not changed by the mirror, so the individual photons in both the transmitted and the reflected beam must have the original energy hν. One concludes that the photons are not split but go into one beam or the other, at random.

If we recombine the two beams in an interferometer (fig. 1) we usually get interference fringes; because of a slight misalignment (often intentional) the phase relation of the two waves as they become superimposed varies from place to place and we get alternate reinforcement and cancellation of the two waves.

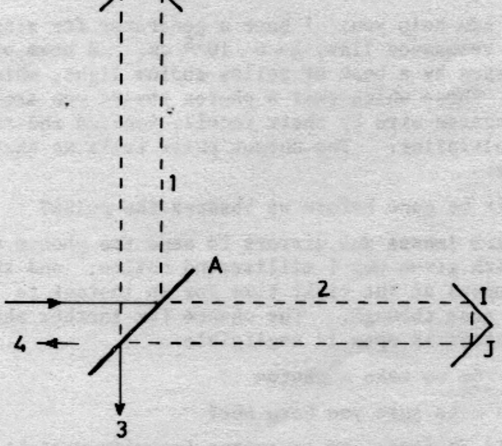

Fig. 1 'Take a photon'.

But it is simpler to discuss an interferometer which is so adjusted that we get no fringes. For instance, if the two right-angle mirror pairs G-H and I-J are placed so that the intersection line of G and H is the exact mirror image (in the half-silvered mirror A) of the intersection line of I and J, then the light waves that pass through A on their return will cancel each other; all the light will go into beam 3 (the reflected beam), while beam 4 will have zero intensity.

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 the 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. Indeed I am in two (or more) minds what to think, and for that reason I find it easiest to present the arguments in a dialogue between several characters. I have compelled them to be brief, but I'll try to elucidate what they say and sum up their findings at the end.

Jim: Take a photon...

Tom: How?

Jim: Well, take a weak light source and open a shutter long enough to let out one photon.

Tom: But you may get two, or none!

Bob: Is it single photons of visible light you want?

Jim: Yes.

Bob: Then I can help you; I have a generator for single photons of the sodium resonance line, $\lambda = 6 \cdot 10^{-5}$ cm. A beam of slow sodium atoms is crossed by a beam of yellow sodium light, which excites some of them. Those which emit a photon toward you are deflected on to a hot tungsten wire by their recoil, ionized and recorded by an electron multiplier. The output pulse tells us that a photon is on the way.

Tom: Won't it be gone before we observe the pulse?

Bob: There are lenses and mirrors to send the photon on a detour of 300 km, which gives you 1 millisecond notice; and there is a shutter which opens at the right time for an instant to let just that one photon pass through. The chance for another photon to arrive while the shutter is open is negligible.

Jim: Fine. So we take a photon...

Tom: Can you make sure you have one?

Bob: There is no need; my generator is quite reliable.

Tom: Still, one ought to be able to make sure there is a photon.

Jim: One could record it with a photomultiplier...

Tom: Not with any certainty!

Bob: True; photocathodes have at best about 30 percent efficiency. But with some semiconductors one can get close on 100 percent. There is some noise, but with deep cooling...

Tom: All right; let us say we have a perfect photon detector. So we can make a photon, know when it will come, and verify that it has come. But in verifying we kill it!

Jim: I know. Still, it seems I may at last say 'take a photon'. It behaves essentially like a particle: it starts from a point, it travels along a line, it...

Bill: Surely not! Light consists of waves; you can at best create a wave packet! And after travelling 300 km...

Bob: Let me give you the scale of my apparatus. My lens has a diameter a of one metre; over the distance $b = 300$ km the wave spreads by about $\lambda b/a$ which comes to 18 cm; the second lens is a little larger to allow for that, and it forms an image just as small as the original source, only a few wavelengths in size. The spread is...

Bill: Essentially nil, I agree. But where does the photon pass through those large lenses of yours?

Jim: I don't care; somewhere. Just let me take my photon from the focus of Bob's second lens. We can consider this as our photon source, and we know - we have 1 millisecond warning - when the photon is coming.

Tom: All right, we'll let you take a photon. What will you do with it?

Jim: I shall split it with a half-silvered mirror.

Bill: But that doesn't split the photon; it is either reflected or transmitted, the chances being half and half.

Jim: So the photon travels either in the direction 1 or 2?

Bill: Sure. If you were to place photon detectors in both beams, either one or the other would record the photon.

Jim: Good. Now please note that I have provided angle mirrors (fig.1) which cause both beams to return and to be recombined.

Bill: I see. You have built an interferometer similar to Michelson's. If your two distances are exactly alike then the reunited beam will go to the detector 3, not 4, if I've got the phase shifts right.

Jim: Correct. From that I conclude that the photon has been split, that it is present in both beams 1 and 2. There is no element of chance. We need both parts of the photon to obtain the interference that causes it to be recorded at 3 and not at 4.

Bill: But how do you account for the fact that of two photon detectors placed in 1 and 2, only one at random - will record the photon?

Jim: It must be the detectors that introduce the randomness.

Bill: You mean that when one detector happens to report the photon, the other one is precluded from doing so?

Jim: Yes.

Bill: Even though the other half of the photon passes through it?

Jim: No. Surely the other half no longer exists, it must have been destroyed when the photon was spotted in the first beam. Only one photon was produced by Bob's source, and a photon can only be absorbed and detected once.

Tom: Isn't that the "reduction of the wave packet" that the theoreticians talk about?

Bob: I suppose so. But what does it mean? How can the observation of a photon in one place destroy the other half of the photon?

Bill: There is no split photon; there is only a wave, which indeed is split.

Bob: I must protest; my generator surely produces photons, one at a time. We agreed to that at the beginning.

Roy: Let me try to remember what I was taught. The wave associated with one photon is not real; it is merely a mathematical tool which allows us to compute the probability that a photon will be observed at a given place. The split wave is just a description of our knowledge that a single photon has entered our interferometer and has met a half-silvered mirror. Once we know that the photon has been observed in one of the beams the probability that it should be found in the other becomes nil.

Jim: Just as the chance for a horse to win a race becomes nil when another horse has won it?

Roy: A bit like that.

Tom: But if it is only a matter of probability that the photon is observed, might it not be missed by both detectors?

Roy: Let us assume the detector in beam 1 is nearer the splitting mirror than the one in beam 2. Then if it records the photon it modifies the wave - which only represents our knowledge - so that 2 has nothing to detect. But if detector 1 remains silent at the critical time, then the wave in beam 2 gets strengthened so that the photon is sure to be recorded there.

Tom: Which detector affects the wave if they are the same distance from the mirror, to within the length of the wavetrain? And anyhow, if the wave represents our knowledge it can only become modified by something that we come to know. What if we don't look at the first detector, but merely arrange for its signal to be recorded?

Roy: Then there will be an even chance - just as if the first detector wasn't there - that the second detector will report the photon.

Tom: Yes; but it will not report the photon in those cases where a later inspection of the first detector shows that it had, unknown to us at the time, recorded the photon. Does the present behaviour of the second detector then depend on the future state of our knowledge about the first one?

Roy: No. We must interpret knowledge in a wider way. When one of the detectors records the photon, then the way it went is 'known' though you and I may not know it.

Bob: This is getting ever more implausible: the knowledge stored in one box of electronics is said to affect a wave elsewhere without signalling! - and so the behaviour of another box. Why not admit that the photon, on meeting the half-silvered mirror, takes a snap decision, at random, whether to go through or be deflected?

Jim: Because then you can't account for the interference. If you were sure that half the photons travel along each path you could block up one of the paths and merely halve the intensity recorded by detector 3. But you know that if you block one path you destroy the interference: you then observe as many photons in detector 4 as in 3, whereas with both paths open all the photons arrive at 3.

Bill: Wouldn't the wave account for the interference? There is both the wave and the photon. The wave gets split while the photon is either transmitted or reflected.

Jim: But if we block one path with a detector and find the photon has gone that way, then you still have a wave travelling along the other path; a futile little wave without a photon! Unless you 'reduce it', and then we are back to where we were.

Tom: Couldn't one spot the photon without absorbing it?

Bob: Certainly. For instance, a transparent block of mass M, thickness a and refractive index n will be displaced forward by the amount $s = a(n-1)\ (h/Mc\lambda)$ when a photon of wavelength λ passes through it. That displacement is small, but...

Bill: I know. However, such a block causes a phase shift of $2\pi(n-1)a/\lambda$ which will affect the interference and may destroy it.

Bob: Can't we choose our block so that the phase shift is $N.2\pi$ where N is an integer? Then it won't affect the interference.

Bill: Let me see. The displacement would come to $s = Nh/Mc$. If we measure to that accuracy we cannot know the momentum of our block to better than h/s (according to Heisenberg's uncertainty principle) or v to better than $h/sM = c/N$. If the block has the velocity v then the time the photon spends in the block is altered by the fraction $v/c = 1/N$, and so is the phase shift. So the phase is uncertain by 2π, and the interference is completely destroyed.

Roy: Look, all this has been threshed out in Copenhagen, in the 'thirties: if you spot the photon you ruin the phase.

Bob: I think I see a way around that. Let me suspend the half-silvered mirror so that we can measure its momentum perpendicular to its own plane...

Roy: That has all been disposed of. If you measure the momentum of the mirror to within h/λ, the momentum of a single photon, its position is uncertain by λ, and that ruins the interference.

Bob: No, wait, I have a new trick. I propose to suspend my mirror with a half-period equal to the time the photon takes to go out and back again along an arm of the interferometer. If it happened to deviate by +d from its equilbrium when the photon first arrived it will deviate by -d when the photon returns. Thus d has no effect on the phase, and the interference will not be ruined: it will happen just as if the mirror had been fixed in its equilibrium position?

Roy: Ingenious. How will you measure the momentum transfer?

Bob: Well, I just measure the momentum before the photon enters and again after it has been recorded at 3. The mirror will have been pushed one way if the photon was reflected at first and transmitted on the way back, and the other way if it followed the other path.

Roy: But in the latter case the push comes half a period later than in the first; and the final outcome is the same whether you push a pendulum in one direction or half a period later in the opposite. So your measurement does not tell you which path the photon has taken!

Bob: Ingenious. I fear you are right. So I must do one of my momentum measurements while the photon is in the interferometer, and that will spoil the interference.

Tom: Still, you have designed a means of observing where the photon is, without doing anything to it; does that not prove that the photon really is in one beam, and not split?

Jim: Einstein said something like that.

Roy: You have not really observed where the photon is, merely by suspending the mirror; you must measure its momentum.

Bob: But the momentum is in the mirror, and I can measure it or not, as I wish; surely that does nothing to the photon?

Roy: Yes, it does; it spoils the interference. All you have done is to share the clue about the position of the photon between the photon and the mirror so that it can be extracted from either of them. Your particular suspension ensures that this clue is automatically destroyed at the moment when the photon, by interference, gets directed to detector 3.

Tom: If the mirror had not been suspended in that way but just left floating, then the momentum transfer would have measured the photon's position?

Bob: Not necessarily. I think I could construct a mechanism by which you could make the mirror go to where the suspension would have taken it, if you so decide before the photon returns. All I need is...

Tom: We'll believe you. But once I have reflected a low-energy photon from the mirror so as to determine its velocity by Doppler shift, then the measurement is done?

Bob: Not necessarily. I might construct a system of mirrors to send back the low-energy photon and return its momentum to the mirror.

Tom: But when *is* the measurement done?

Bob: I think any reversible process can be reversed. But I would regard myself as beaten if you have let the system interact irreversibly with say, a semiconductor, a photographic grain, or a retina.

Tom: That makes sense. After all, to measure is to create information; and information is a state in a machine or an organism - which extends from a certain time into the future. Irreversibility is the very essence of information.

Jim: But don't we sometimes obtain information without irreversible interaction? For instance, when the detector in beam 1 reports nothing we know that the photon is in beam 2.

Bob: Yes; but the detector has to be there, in beam 1; the possibility of an irreversible interaction is essential.

Jim: What if I place a piece of black paper into one beam? Then we have an irreversible interaction and we destroy the interference without getting any information in return.

Bob: Not necessarily; you could measure the temperature of the paper before and after!

Jim: But what if I don't?

Bob: Oh well, information can get lost if you are careless.

Jim: But, information aside, what does the photon do in my interferometer; does it get split, or doesn't it?

Roy: You musn't say 'information aside'. Quantum theory is about information. All it does is to tell you how to use available information to make the best possible predictions about future information.

Jim: You mean, about what is going to happen?

Bob: If you agree to use the word 'to happen' only for irreversible processes.

Tom: Surely something happens - in the everyday sense - to the photon inside the interferometer; so quantum theory must be incomplete.

Roy: I don't feel that. Quantum theory is logically consistent, and it allows you to make all the predictions that you can test. Photons and waves are models that allow you to use your imagination instead of using the full theory, but they cannot completely replace it.

Bill: Couldn't one have a model that covers both photons and waves? Something more complex, perhaps multidimensional, of which our present concepts are merely flat projections?

Roy: Plato's cave. Well, produce such a model, and we'll discuss it next time.

Jim: But there are some worse difficulties which today we haven't even touched on. Take two photons...

Here we must break off the discussion and see what has been achieved. First we must admit that many of Bob's ambitious gadgets will never be built. That need not worry us; the use of thought experiments ('Gedanken-Experimente') in physical arguments has a long history and is generally accepted. Of course a thought experiment may be faulty if it contains an essential snag that has been overlooked by its designer. (A famous example was a thought experiment designed by Einstein and refuted by Bohr in 1930). I have allowed Bob to explain his photon generator in some detail because photons are emitted at random, and some people have suggested that any thought experiment must be faulty if it assumes that we 'take a photon'. I think Bob has dispelled that idea. He cannot produce a photon at a specified time; but if Jim is willing to wait he will get one photon at a time and will know (a millisecond in advance) when it will arrive.

After that, the discussion turns to the question, what happens to the photon on striking the half-silvered mirror? Jim believes that it is split; Tom doubts it; Bill suggests that merely the wave is split. None of the attempted ways of visualizing what happens inside an interferometer appears satisfactory. The most common way is the one put forward by Roy, that the wave - which is split - determines the probability of the photon being intercepted in either beam 1 or 2. But then one has to assume that if the photon is found in, say, beam 1 the wave packet which represented the probability of finding it in beam 2 is thereby reduced to zero. This "reduction of the wave packet" is not a physical process in the ordinary sense; it happens instantly, however far the two wave packets may be apart at the time when the photon is found in one of them.

Roy suggests that we should take the wave merely as a representation of what we know about the photon. Then the reduction process seems easier to understand; the wave packet becomes comparable to a list of betting odds which drop to zero as soon as a different contestant is known to have won the race. But it is not just a matter of our knowledge (say, that one detector has reported the photon) affecting our belief (concerning the chance of the other detector reporting it). We can place ideal photon detectors into both beams and record their signals; afterwards we can verify that every photon admitted was recorded by either one or the other of the two detectors. If we use the idea of a wave that is split we must assume collusion between the detectors (which is what the "reduction of the wave packet" amounts to).

Yet we cannot simply assume - as Tom suggests that each photon is either transmitted or reflected; if that were so we could not account for the interference, that is, for the fact that all the photons emerge in beam 3 and not 4, provided both paths are kept open. If we want to visualize what causes the interference, we must think of a wave that is split by the half-silvered mirror and explores both paths.

Those two descriptions a wave that is split and capable of interference, and a photon that is at random either transmitted or reflected - are called *complementary* aspects of the same thing, according to Niels Bohr. According to that view it is up to the physicist to choose that description which is appropriate to a given experimental situation. For the interferometer the wave picture is appropriate; if detectors are used to monitor the two beams (or even one of them) then the photon picture is appropriate. But there are intermediate situations (not discussed here) when neither picture is adequate, and then the mathematical theory must be wheeled into position.

The discussion then turned to the question whether the photon might not be spotted in one of the two beams without being absorbed. That is indeed possible (at least in the realm of thought experiments). For instance, a photon entering a block of glass changes its momentum from h/λ to $h/n\lambda$; the difference in momentum $(n-1)h/\lambda n$ is given to the glass block and causes it to move forward with the speed $(n-1)h/\lambda Mn$. After the time an/c the block stops again as the photon emerges from it; it has thus travelled the distance $(n\ \ 1)ah/cM\lambda$ (as Bob says).

But even though we have not absorbed the photon we have lost the chance of observing interference. Heisenberg's uncertainty principle tell us that the speed of the glass block will be uncertain by $\Delta v = \Delta p/M = h/Ms$ if we know its position to the accuracy s. That speed affects the time the photon spends in the block and hence the phase shift by just enough to make it uncertain whether the photon will go into beam 3 or 4. So once again, if we locate the photon we no longer observe the phenomenon - interference - which caused Jim to believe that the photon gets split.

At that point the inventive Bob comes up with a variant of the movable-mirror idea. His special suspension fails to allow him - as he first thought - to spot the photon and still to retain the interference. But it gives him liberty to choose: he can measure the momentum of the mirror (say by reflecting a low-energy - i.e. long-wave - photon from it and measuring the change, due to Doppler effect, of its wavelength) before the photon has returned from one of the two angle mirrors, and that will tell him which way it went; or, if he does nothing, the mirror will swing in such a way that the interference is not disturbed. This is really a model of the EPR paradox (Einstein, Podolski and Rosen 1935), namely the fact (demonstrated mathematically in that paper) that one can create situations in which one has the choice of measuring either the momentum or the position of a given particle "without physically affecting that particle". But that final clause (in inverted commas) doesn't really create a paradox once we have accepted that "the same thing" - a photon that has met a half-silvered mirror - requires two totally different descriptions, depending on whether we have arranged to locate the photon or to observe interference (Bohr 1935). Again, there is nothing new in Bob's suspended mirror, merely a concrete example of something that is hard to think about. More severe forms of the EPR paradox exist (Furry, Dicke and Wittke, Frisch) and Jim wanted to talk about them, but I had to cut him off.

Perhaps the most important conclusion arises out of the insistence of Bob that "any reversible process can be reversed", given enough ingenuity. The conclusion is that a measurement is not done until some irreversible process has taken place, such as an interaction with a grain in a photographic emulsion. Let me repeat what Tom says: "To measure is to create information, which is a state - in a machine or an organism - which extends from a certain time into the future". The intimate connection between information and irreversibility has indeed been stressed by L. Brillouin.

The main thing, as Roy points out, is that we must not ask what a quantum system does between observations. Quantum theory tells us how to use available information to make predictions about future information, and there are reasons to think (J. von Neumann) that they are the best possible predictions. I still feel a bit uneasy because I see no clear way of drawing the line between irreversible interactions which create (at least potentially) information and are to that extent 'real', and those interactions - like that between a photon and a half-silvered mirror - which don't create information and are 'unreal', demanding different descriptions in different circumstances.

As to Tom's last suggestion, of a possible model of which our present concepts such as waves and photons - are merely shadows like those in Plato's cave, I have some sympathy with it; but no such model appears to be in sight.

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The dialogue that forms the centre-piece was written for the 70th birthday (on 15th September 1964) of Professor Oskar Klein, Stockholm, one of the pioneers of quantum theory, whose name is familiar from the Klein Paradox, the Klein-Gordon Wave equation and the Klein-Nishina formula.

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