Light reconsidered

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> *I therefore take the liberty of proposing for this hypothetical new atom, which is not light but plays an essential part in every process of radiation, the name* photon.[1]
> Gilbert N. Lewis, 1926

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Light is an obvious feature of everyday life, and yet light's true nature has eluded us for centuries. Near the end of his life Albert Einstein wrote, "All the fifty years of conscious brooding have brought me no closer to the answer to the question: What are light quanta? Of course today every rascal thinks he knows the answer, but he is deluding himself." We are today in the same state of "learned ignorance" with respect to light as was Einstein.

In 1926 when the chemist Gilbert Lewis suggested the name "photon," the concept of the light quantum was already a quarter of a century old. First introduced by Max Planck in December of 1900 in order to explain the spectral distribution of blackbody radiation, the idea of concentrated atoms of light was suggested by Einstein in his 1905 paper to explain the photoelectric effect. Four years later on September 21, 1909 at Salzburg, Einstein delivered a paper to the Division of Physics of German Scientists and Physicians on the same subject. Its title gives a good sense of its content: "On the development of our views concerning the nature and constitution of radiation."[2]

Einstein reminded his audience how great had been their collective confidence in the wave theory and the luminiferous ether just a few years earlier. Now they were confronted with extensive experimental evidence that suggested a particulate aspect to light and the rejection of the ether outright. What had seemed so compelling was now to be cast aside for a new if as yet unarticulated view of light. In his Salzburg lecture he maintained "that a profound change in our views on the nature and constitution of light is imperative," and "that the next stage in the development of theoretical physics will bring us a theory of light that can be understood as a kind of fusion of the wave and emission theories of light." At that time Einstein personally favored an atomistic view of light in which electromagnetic fields of light were "associated with singular points just like the occurrence of electrostatic fields according to the electron theory." Surrounding these electromagnetic points he imagined fields of force that superposed to give the electromagnetic wave of Maxwell's classical theory. The conception of the photon held by many if not most working physicists today is, I suspect, not too different from that suggested by Einstein in 1909.

Others in the audience at Einstein's talk had other views of light. Among those who heard Einstein's presentation was Max Planck himself. In his recorded remarks following Einstein's lecture we see him resisting Einstein's hypothesis of atomistic light quanta propagating through space. If Einstein were correct, Planck asked, how could one account for interference when the length over which one detected interference was many thousands of wavelengths? How could a quantum of light interfere with itself over such great distances if it were a point object? Instead of quantized electromagnetic fields Planck maintained that "one should attempt to transfer the whole problem of the quantum theory to the area of *interaction* between matter and radiation energy." That is, only the exchange of energy between the atoms of the radiating source and the classical electromagnetic field is quantized. The exchange takes place in units of Planck's constant times the frequency, but the fields remain continuous and classical. In essence, Planck was holding out for a semi-classical theory in which only the atoms and their interactions were quantized while the free fields remained classical. This view has had a long and honorable history, extending all the way to the end of the 20th century. Even today we often use a semi-classical approach to handle many of the problems of quantum optics, including Einstein's photoelectric effect.[3]

The debate between Einstein and Planck as to the nature of light was but a single incident in the four thousand year inquiry concerning the nature of light.[4] For the ancient Egyptian light was the activity of their god Ra seeing. When Ra's eye (the Sun) was open, it was day. When it was closed, night fell. The dominant view in ancient Greece focused likewise on vision, but now the vision of human beings instead of the gods. The Greeks and most of their successors maintained that inside the eye a pure ocular fire radiated a luminous stream out into the world. This was the most important factor in sight. Only with the rise of Arab optics do we find strong arguments advanced against the extromissive theory of light expounded by the Greeks. For example around 1000 A.D. Ibn al-Haytham (Alhazen in the West) used his invention of the *camera obscura* to advocate for a view of light in which rays streamed from luminous sources traveling in straight lines to the screen or the eye.

By the time of the scientific revolution the debate as to the physical nature of light had divided into the two familiar camps of waves and particles. In broad strokes Galileo and Newton maintained a corpuscular view of light, while Huygens, Young and Euler advocated a wave view. The evidence supporting these views is well known.

The elusive single photon

One might imagine that with the more recent developments of modern physics the debate would finally be settled and a clear view of the nature of light attained. Quantum electrodynamics (QED) is commonly treated as the most successful physical theory ever invented, capable of predicting the effects of the interaction between charged particles and electromagnetic radiation with unprecedented precision. While this is certainly true, what view of the photon does the theory advance? And how far does it succeed in fusing wave and particle ideas? In 1927 Dirac, one of the inventors of QED, wrote confidently of the new theory that, "There is thus a complete harmony between the wave and quantum descriptions of the interaction."[5] While in some sense quantum field theories do move beyond wave particle duality, the nature of light and the photon remains elusive. In order to support this I would like to focus on certain fundamental features of our understanding of photons and the philosophical issues associated with quantum field theory.[6]

In QED the photon is introduced as the unit of excitation associated with a quantized mode of the radiation field. As such it is associated with a plane wave of precise momentum, energy and polarization. Because of Bohr's principle of complementarity we know that a state of definite momentum and energy must be completely indefinite in space and time. This points to the first difficulty in conceiving of the photon. If it is a particle, then in what sense does it have a location? This problem is only deepened by the puzzling fact that, unlike other observables in quantum theory, there is no Hermetian operator that straightforwardly corresponds to position for photons. Thus while we can formulate a well-defined quantum-mechanical concept of position for electrons, protons and the like, we lack a parallel concept for the photon and similar particles with integer spin. The simple concept of spatio-temporal location must therefore be treated quite carefully for photons.

We are also accustomed to identifying an object by a unique set of attributes. My height, weight, shoe size, etc. uniquely identify me. Each of these has a well-defined value. Their aggregate is a full description of me. By contrast the single photon can, in some sense, take on multiple directions, energies and polarizations. Single-photon spatial interference and quantum beats require superpositions of these quantum descriptors for single photons. Dirac's refrain "photons interfere with themselves" while not universally true is a reminder of the importance of superposition. Thus the single photon should *not* be thought of as like a simple plane wave having a unique direction, frequency or polarization. Such states are rare special cases. Rather the superposition state for single photons is the common situation. Upon detection, of course, light appears as if discrete and indivisible possessing well-defined attributes. In transit things are quite otherwise.

Nor is the single photon state itself easy to produce. The anti-correlation experiments of Grangier, Roger and Aspect provide convincing evidence that with suitable care one can prepare single-photon states of light.[7] When sent to a beam splitter such photon states display the type of statistical correlations we would expect of particles. In particular the single photons appear to go one way or the other. Yet such single-photon states can interfere with themselves, even when run in "delayed choice."[8]

More than one photon

If we consider multiple photons the conceptual puzzles multiply as well. As spin one particles, photons obey Bose-Einstein statistics. The repercussions of this fact are very significant both for our conception of the photon and for technology. In fact Planck's law for the distribution of blackbody radiation makes use of Bose-Einstein statistics. Let us compare the statistics suited to two conventional objects with that of photons. Consider two marbles that are only distinguished by their colors: red (R) and green (G). Classically, four distinct combinations exist: RR, GG, RG and GR. In writing this we presume that although identical except for color, the marbles are, in fact, distinct because they are located at different places. At least since Aristotle we have held that two objects cannot occupy exactly the same location at the same time and therefore the two marbles, possessing distinct locations, are two distinct objects.

Photons by contrast are defined by the three quantum numbers associated with momentum, energy and polarization; position and time do not enter into consideration. This means that if two photons possess the same three values for these quantum numbers they are indistinguishable from one another. Location in space and in time is no longer a means for theoretically distinguishing photons as elementary particles. In addition, as bosons, any number of photons can occupy the same state, which is unlike the situation for electrons and other fermions. Photons do not obey the Pauli Exclusion Principle. This fact is at the foundation of laser theory because laser operation requires many photons to occupy a single mode of the radiation field.

To see how Bose-Einstein statistics differ from classical statistics consider the following example. If instead of marbles we imagine we have two photons in our possession which are distinguished by one of their attributes, things are quite different. For consistency with the previous example I label the two values of the photon attribute R and G. As required by Bose-Einstein statistics, the states available to the two photons are those that are symmetric states under exchange: RR, GG and $^1\!/_2$(RG + GR). The states RG and GR are non-symmetric, while the combination $^1\!/_2$(RG – GR) is anti-symmetric. These latter states are not suitable for photons. All things being equal we expect equal occupation for the three symmetric states with 1/3 as the probability for finding a pair of photons in each of the three states, instead of $^1\!/_4$ for the case of two marbles. This shows that it makes no sense to continue to think of photons as if they were "really" in classical states like RG and GR.

Experimentally we can realize the above situation by sending two photons onto a beam splitter. From a classical perspective there are four possibilities. They are sketched out in Fig. 1. We can label them RR for two right-going photons, UR for up and right, RU for right and up, and UU for the two photons going up. The quantum amplitudes for the UR and RU have opposite signs due to the reflections which the photons undergo in Fig. 1c, which leads to destructive interference between these two amplitudes. The signal for one photon in each direction therefore vanishes. Surprisingly both photons are always found together. Another way of thinking about the experiment is in terms of the bosonic character of photons. Instead of thinking of the photons as having individual identities we should really think of there being three ways of pairing the two photons: two up (UU), two right (RR) and the symmetric combination (1/2(UR + RU)). All things being equal, we would expect the experiment to show an even distribution between the three options, 1/3 for each. But the experiment does not show this; why not? The answer is found in the opposite signs associated with UR and RU due to reflections. As a consequence the proper way to write the state for combination of b and c is $^1/_2$(UR – RU). But this is antisymmetric and therefore forbidden for photons which must have a symmetric state.

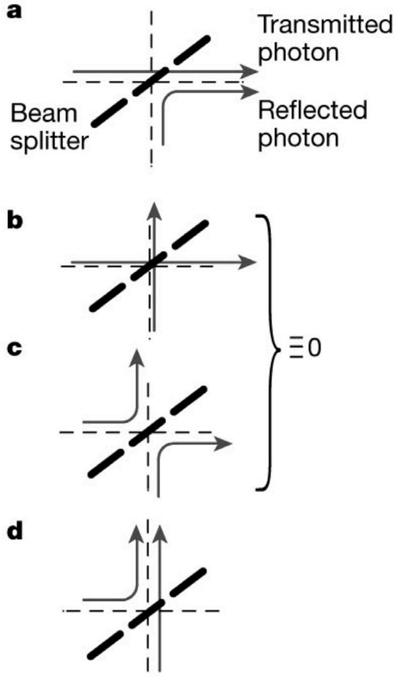

Fig. 1. Copyright permission granted by *Nature*.[9]

From this example we can see how Bose statistics confounds our conception of the identity of individual photons and rather treats them as aggregates with certain symmetry properties. These features are reflected in the treatment of photons in the formal mathematical language of Fock space. In this representation we only specify how many quanta are to be found in each mode. All indexing of individual particles disappears.

Photons and relativity

In his provocatively titled paper "Particles do not Exist," Paul Davies advances several profound difficulties for any conventional particle conception of the photon, or for that matter for particles in general as they appear in relativistic quantum field theory.[10] One of our deepest tendencies is to reify the features that appear in our theories. Relativity confounds this habit of mind, and many of the apparent paradoxes of relativity arise because of our erroneous expectations due to this attitude. Every undergraduate is confused when, having mastered the electromagnetic theory of Maxwell he or she learns about Einstein's treatment of the electrodynamics of moving bodies. The foundation of Einstein's revolutionary 1905 paper was his recognition that the values the electric and magnetic fields take on are always relative to the observer. That is, two observers in relative motion to one another will record on their measuring instruments different values of E and B for the same event. They will, therefore, give different causal accounts for the event. We habitually reify the electromagnetic field so that particular values of E and B are imagined as truly extant in space independent of any observer. In relativity we learn that in order for the laws of electromagnetism to be true in different inertial frames the values of the electric and magnetic fields (among other things) must change for different inertial frames. Matters only become more subtle when we move to accelerating frames.

Davies gives special attention to the problems that arise for the photon and other quanta in relativistic quantum field theory. For example, our concept of reality has, at its root, the notion that either an object exists or it does not. If the very existence of a thing is ambiguous, in what sense is it real? Exactly this is challenged by quantum field theory. In particular the quantum vacuum is the state in which no photons are present in any of the modes of the radiation field. However the vacuum only remains empty of particles for inertial observers. If instead we posit an observer in a uniformly accelerated frame of reference, then what was a vacuum state becomes a thermal bath of photons for the accelerated observer. And what is true for accelerated observers is similarly true for regions of space-time curved by gravity. Davies uses these and other problems to argue for a vigorous Copenhagen interpretation of quantum mechanics that abandons the idea of a "particle as a really existing thing skipping between measuring devices."

To my mind, Einstein was right to caution us concerning light. Our understanding of it has increased enormously in the 100 years since Planck, but I suspect light will continue to confound us, while simultaneously luring us to inquire ceaselessly into its nature.

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