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The nature of light: what are photons?

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Understanding that superposition effects are due not to electromagnetic field-field but to field-detector interactive processes has many practical implications.

(a) (b)

Figure 1. *Wave forms pass through each other without mutual interference. (a) In a sports stadium, light and sound beams transport complex information unperturbed even after they are crossed by innumerable other complex beams. (Photo courtesy of Catherine Seaver.) (b) Two groups of circular water waves, generated by dropping two stones, pass through each other preserving their intrinsic characteristics. Fringes are visible only within the physical domains of superposition. (Image freely available on the Web.)*

Introduction

What do we mean by interference—or the superposition effect—of light? For centuries we have used the word 'interference' to describe the dark-bright bands recorded when we superpose two coherent light beams at a small angle on a detector. Indeed, holograms are such fringes caused by superposition of an 'object beam' with a coherent and uniform reference beam recorded on a very-high-resolution photographic plate.

Physicist Sir Roger Penrose recently underscored the lack of reality in our current theories about how the world works.[1] We would respond that reality is whatever we can actually sense and measure, even if that amounts to only a tiny fraction of the enormously complex jigsaw puzzle we call the cosmos. In our everyday experience, light beams pass through each other unperturbed without interacting (interfering) with each other unless we try to detect them. Taking this mundane observation into account increases the potential for innovative applications in technology, while resolving the problem of wave-particle duality for photons.

Why ask the question?

There is an extensive literature dealing with quantum communication, computation, and encryption using devices that produce, manipulate, propagate, and detect 'single photons.' The definition of a photon given by quantum mechanics (QM) enjoys wide acceptance because of its great predictive power. Yet QM does not help us to imagine and visualize the interactive processes that ultimately produce measurable single-quantum events.[2] All detectors consist of atoms and molecules whose energy levels are quantized. Electrons are indivisible, and their binding energies are quantized. Thus their response to light can only be registered as discrete quantum events irrespective of whether light energy constitutes indivisible photons. Light beams always travel with a finite velocity carrying a finite flux density delivering energy in time. Any registration of light energy patterns will therefore always be built up as accumulated discrete quantum events whose temporal rate will be proportional to the incident flux rate. A low photoelectron count rate is insufficient proof of the indivisibility of photons.

Mathematics is not physics

Nature has evolved through continuous, interactive processes that cannot be neatly divided into classical, relativistic, or quantum-mechanical systems. Mathematical tool sets devised by humans help us to solve all these small, separate pieces of the puzzle of the universe. But fitting them into a larger logical pattern means that we must restructure them. Here, again, mathematics is the best integrating tool because it is the most objective and logical, yet mathematics by itself has so far been unable to carry the task through. Mathematics and science are

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not the same thing. When a tool proves unsuitable, it is better to invent another rather than to force an interpretation on nature.

In restructuring the smaller solved puzzles, we need to use our imagination to find better conceptual continuity between them by imposing a newer logical congruence. What we measure is always an effect on both the sensor and the sensee through the exchange of energy between them. None of our measurements—classical or quantum—can be exact. All that successful equations from any theory, including QM, can do is to predict the outcome of a well-designed experiment. Understanding and visualizing the deeper physical processes underpinning interactions depend on human imagination and interpretation. That is the real objective (or purpose) of the discipline we call physics. Our job is to connect the symbols of successful mathematical relations with the physical states of actual entities and the operators with the allowed interactive processes. We call such Newtonian thinking reality ontology.[2]

Returning to observation

All waves pass through each other unperturbed. Failure to take this prosaic observation into account in our scientific models is at the root of many conceptual paradoxes in modern science and philosophy. In a sports stadium—see Figure 1(a)—you can easily focus your television camera and the acoustic telescope to pick up the voice and image of the referee at a distance. You can record the image and voice even though the relevant beams are crossed by thousands of other light and acoustic beams. How, then, do we see 'interference patterns' such as those in Figure 1(b)?

Water and sound waves are manifest through the physical undulations of some observable material medium that also makes the superposition effects 'visible.' Unfortunately, we cannot directly see the cosmic medium in which light is an undulation, and that makes the superposition effect rather elusive. Nonetheless, light is a form of wavelike energy since its superposition and diffraction effects are very much like those displayed by water and sound waves. Propagation of all these waves is accurately predicted using the same Huygens-Fresnel (HF) diffraction integral. From the design and construction of the Hubble Telescope to modeling and fabricating the latest nanophotonics devices, the HF principle has guided us quite successfully without assuming photons to be indivisible packets of energy. The success of this principle also tells us that light waves are collective phenomena. When a well-formed wave front is perturbed, it collectively rearranges itself through the near-field propagation zone into a new, sustainable, and steady-state far-field beam whose angular distribution remains constant during further propagation.

Light is a form of propagating harmonic undulation of an electromagnetic (EM) stress gradient in the cosmic medium. It is not a waterlike wave of the cosmic medium itself. When you hold a magnet, you create an invisible magnetic field gradient around it. When you move it, you create a changing field gradient, but it remains local. In contrast, once generated, a harmonic EM stress gradient must always propagate with a finite velocity. Maxwell's wave equation corroborates this model by representing the EM field as a propagating vector potential whose velocity depends on the dielectric constant and magnetic permeability of the medium (whether embedded by atoms and molecules, or free cosmic space). We only see light through the 'eyes' of different material detectors and only when their quantum properties allow them to absorb energy from a particular electromagnetic (EM) field.

Because most light emitters are space, time, and energy finite atoms and molecules, the emitted photons must also be space, time, and energy finite. Do photons propagate as indivisible packets of energy or as spreading and diffracting wave packets? A photon certainly is a mode of oscillation of an EM stress field in the cosmic medium. But can a mathematical Fourier monochromatic mode that exists over all space and time map the physical reality of a photon? Let us look at some obvious paradoxes.

We can now appreciate that two light beams containing trillions of photons do not redistribute their energy density when they are made to cross through each other. Thus, when intensity is drastically reduced, how can a single photon from these beams make itself appear or disappear on a detector array to build up the fringes? The detecting dipole molecule tries to undulate in response to both superposed EM stimulations. Dark fringes are found where the fields are 180° out of phase because the detecting dipoles cannot undulate in two opposing directions at the same moment. They are not stimulated and hence cannot absorb energy from the fields. The field energy (photons) are not absent from these locations. They simply cannot be absorbed. Bright fringes are found where the two fields stimulate the dipole undulations in phase and in the same direction, maximizing the absorption of energy. The operation or 'summation' of amplitudes and phases, represented by the superposition equation, is carried out by the detecting dipoles, not by the two fields themselves. Superposition fringes are *locally* created by the subnanometer-size detecting molecules!

Albert Michelson's Fourier transform spectrometer works because the molecules of the dielectric beam-splitter surface cannot simultaneously respond to the joint effects due to superposed different frequencies. The molecules respond to different frequencies separately, as if the fields were incoherent to each other. Fiber-optic wavelength-division-multiplexing (WDM) technology works because the different frequencies are propagating

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through a passive fiber without interacting with each other. But when two optical beams containing two different optical frequencies are collinearly superposed on a fast energy-absorbing photoelectric detector, a heterodyne beat current undulating at the difference frequency is generated, as if they were coherent. The paradox can be resolved by focusing our imagination on the interaction process experienced by using molecules.[2] The concept of non-interference of light beams is more than just semantics.

The solutions for Maxwell's wave equation can be any simple sinusoid or a linear combination of them. But 'linear combination' implies a summation operation that cannot be carried out by EM fields. EM sinusoids activate the susceptibility of atoms and molecules to dipolar undulations governed by rules of QM. The formalism of linear combination becomes physically manifest only for the QM-allowed sinusoids through the detecting dipoles, but each multiplied by the characteristic first-order (linear) susceptibility factor. The rest of the sinusoids contribute to weak nonlinear effects governed by nonlinear susceptibilities. *Even for a very successful mathematical formalism, like Maxwell's wave equation, all of its mathematical rules cannot be taken for granted as representing nature's actual processes.*

Mathematically, the time-frequency Fourier theorem allows one to synthesize a pulse or to analyze a pulse as a 'linear superposition' of sinusoids. The 'linearity' of the summation applied to 'linear physical systems' is considered as the justification. Unfortunately, the pure mathematical logic of linearity cannot override the need for real physical processes in the absence of interaction between EM fields. Yet the success of Fourier theorem has been staggering, given that most material-based classical physical undulations (waves, pendulums, and so on) and QM systems can be represented by sinusoids. This is achieved by ad hoc customization of definitions for the Fourier conjugate variables according to the problem. We know that 'mode locking,' or synthesizing a pulse out of the cavity 'modes' can be achieved only with the help of saturable absorbers or their equivalent. The time-frequency bandwidth limit $\delta\nu\delta t \geq 1$ is justified by the same theorem using 'decomposition' logic. But a noninteracting linear system (classical spectrometers) cannot do the actual decomposition. Therefore, this 'bandwidth limit' cannot be a principle of nature, which we have demonstrated as spectral super resolution for an amplitude modulated (AM) pulse using heterodyne spectroscopy.[3] Appreciating this reality should open up the possibility of designing spectrometers with super resolution and a better understanding of natural linewidths.

Conclusion

Science has been slowly moving away from its original goal of visualizing the physical processes at work in nature.[1] We have been so overwhelmed by the prolonged achievements of elegant mathematics that we have consistently ignored our everyday observation that waves by themselves do not form interference fringes. They need some interacting medium to become manifest.[2] *There is no 'interference of light,' there are only 'superposition effects due to light.'*

Please join us at the second biannual conference on The Nature of Light: What Is a Photon? to be held during the SPIE Annual Conference in San Diego, 26–30 August 2007.

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2. C. Roychoudhuri, *Locality of superposition principle is dictated by detection processes*, **Phys. Essays 28** (3), 2006, in press.
3. Other relevant papers by the author with supporting experimental and analytical work are available at http://www.phys.uconn.edu/ chandra/