The photon with a classical field

Abstract:

A model of the photon is proposed which would account for differences between the semiclassical and quantum theories of electromagnetic radiation. The evidence opposing this model is shown to be inconclusive. Guidelines for a more precise experimental test are outlined.

Introduction

Interference experiments which employ low intensity light beams from independent sources have been the subject of considerable discussion in the past (Pfleegor & Mandel, 1967; Radloff, 1968; Radloff, 1971; Mandel, 1976; Liebowitz, 1970; de Broglie & Andrade e Silva, 1968). The results are adequately explained by quantum theory if interference is associated with the detection process, as a superposition of different states of the same photon (Mandel, 1976). Dirac's statement that ". . . each photon interferes only with itself" (Dirac, 1958) is thereby upheld; however, the "detection process" of a photon must then be thought of as occurring over a time period of classical duration, or $\sim 10^{-7}$ seconds (Liebowitz, 1970). Conceptual difficulties of this nature are avoided by the semiclassical theory which attributes classical properties to radiation and quantum mechanical properties to the emission and absorption of radiation. However semiclassical theory encounters much more serious difficulties because it does not ensure energy conservation (Mandel, 1976; Clauser, 1972; Clauser, 1974).

I. A model of the photon

The obvious advantages of both the quantum and the semiclassical theories within certain well-defined contexts has led to a continued search for experiments which support one or the other (Karp, 1976; Mandel, 1977). In this paper we propose an alternative theory in which the photon incorporates features from both the semiclassical and quantum mechanical theories. Let the photon possess the properties of a classical wave packet, but with a discrete energy and a cross sectional area equal to the square of the wavelength (see Karp, 1975; Sillito, 1957). In other words, the photon, like other particles, is conceived of as possessing both discrete and continuous properties. The continuous properties are associated with a classical electromagnetic wave, and in the case of light are manifested experimentally by effects related to the coherence length. Photodetections are often cited as evidence of the photon's discrete energy, but they are associated here with the instantaneous field intensity of single photons or superposed photons. Thus interference fringes are interpreted as arising due to an overlapping of photons, or equivalently wave packets. Since the instantaneous probability of photodetection is proportional to the instantaneous classical intensity of the light (Mandel & Wolf, 1965), the source of a given photon detection will not be identifiable. Indeed it may be stated, without contradicting our previous assertion of a discrete photon energy, that each detection event originates in both sources. The above model of the photon combines attributes of classical waves and classical particles, therefore it is also well suited to account for the fluctuations of photoelectric counts in light beams - which may always be expressed in terms of the fluctuations of classical particles and the fluctuations of classical waves (Mandel & Wolf, 1965).

II. Experimental evidence

The experimental evidence opposing this model is comprised of a single, much discussed experiment, the interference of low intensity light (Taylor, 1909; Dempster & Batho, 1927; Dontsov & Baz, 1967; Reynolds et al., 1969; Grishaev et al., 1971). The validity of this experiment as proof that a photon interferes only with itself depends largely upon whether the intensity of the light beam is sufficiently low to ensure statistically independent photons. Estimates of the attenuation necessary for "low" intensity light are based on time averages of the beam intensity, thus

$$N = c/L_c = 10^9 \text{ photons/sec}$$

where L_c is the coherence length of the photons and c is the speed of light (Reynolds et al., 1969; Grishaev et al., 1971). The actual correlation of photons in a beam of light, however, is determined by the maximum instantaneous intensity of the beam. Intensity fluctuations were first predicted in terms of the angular and spatial correlation of spontaneously emitted photons (Dicke, 1954), and were first observed experimentally as time correlated photons, or photon "bunches" (Brown & Twiss, 1956). Thus photons emitted spontaneously may generate coherent pulses of small cross sectional area and extremely high intensity within a time averaged incoherent beam of overall low intensity. Time averages of a light beam's intensity tell us nothing about the statistical distribution of photons, even for a low density source. Unfortunately the resolution times of photodetectors are many orders of magnitude too slow to measure the intensity "instantaneously". Moreover, the correlation of photon emission, or superfluorescence, is not well understood, even under carefully controlled experimental conditions (Vrehen & Gibbs, 1978).

It is evident from the above arguments that current estimates of the average intensity required for statistically independent photons are not well conceived. A more positive test of the duality principle is performed by comparing the visibility of fringes as the exposure time is increased, the time integrated intensity remaining constant. If the overlapping of photons in weak intensity light is random, the fringe visibility will fall off according to the exponential law, in the manner of visibility curves produced by path differences (see Born & Wolf, 1959). In that case, the attenuation factor times two gives a lower limit for the number of photons in a correlated group. A study of the fringe visibility for intensity differences would then extend the use of the intensity interferometer in the same way that path difference studies extend the use of the Michelson interferometer. On the other hand, should the photon indeed interfere with itself, fringe visibility will be found to be independent of observation time, after compensation has been made for spurious radiation. The advantage of the above experimental test is that it can be used to determine the photon's physical nature decisively without the use of arbitrary estimates.

Of the interference experiments performed with low intensity light, only two normalized the exposures relative to the total intensity (Taylor, 1909; Grishaev et al., 1971), while no experiment attempted to determine the visibility curve due to intensity differences. The fringe visibility of low intensity light is known to decrease in interference experiments performed with image intensifiers, however it has been argued that this effect is caused by "dark current" (Reynolds et al., 1969; Grishaev, 1971). The previous discussion indicates that a decrease in fringe visibility may also be attributed to photon bunching. It is of importance therefore to determine the cause of the observed reductions of fringe visibility directly by plotting the visibility function.

Error due to background radiation may be corrected by using film rather than an image intensifier to record interference fringes. The true visibility of the fringes is then given by,

$$V = V' \{1 + 2e/ D_{max} + D_{min}\}$$

where D is the intensity of the fringes, e is the background intensity, and V' is the measured fringe visibility (Michelson, 1892).

III. Discussion

As has been pointed out in the past, quantum theory cannot be used to analyze the duality principle because duality is itself an inherent property of that theory (Radloff, 1971; Bohm & Bub, 1966). A model of the photon which is not embraced by quantum theory yet accounts for the photon's dual nature may perhaps be used to test the principle of duality (de Broglie & Andrade e Silva, 1968). The proposed model satisfies these conditions and is shown to indicate the above experiment as a test. Indeed quantum theory, semiclassical theory, and that of de Broglie and Andrade e Silva (1968) all predict that the visibility of fringes will be the same irrespective of the intensity of the source, i.e. the visibility function will be a straight line. Only if the photon is a true particle will visibility fall off as intensity is decreased.

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