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DIFFRACTION OF STATISTICALLY INDEPENDENT PHOTONS FROM A LASER SOURCE

E. PANARELLA

National Research Council, Ottawa, K1A OR6, Canada.

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Abstract

The postulate that a photon is a wave-packet accounts for several experiments of diffraction of statistically independent photons. The interpretation, however, of these experiments has not taken into account the fact that optical detectors are unable to reveal the arrival of isolated photons. Moreover, this definition implies that a diffraction pattern is a linear superposition of the patterns formed by each and every independent photon. We have recently performed an experiment of diffraction with photons having strong statistical independence (any two photons were separated by a distance of 6.99×10^5 cm) and have observed that the diffraction pattern did not build up linearly with the number of photons reaching the detector. Actually, the diffraction pattern did not appear at all, although the exposure time exceeded two weeks. In order to justify these results, it is suggested that the wave-packet model for the photon should be replaced by a model of packets of photons.

1. INTRODUCTION

The foundation of quantum theory rests on the notion that a particle is a localised wave-packet formed from the superposition of plane waves of many different frequencies, all grouped around some central frequency(1). The wave-packet carries the particle's energy-momentum at the group velocity and is completely specified by an amplitude function $\psi(x,t)$, where $|\psi(x,t)|^2$ is interpreted as the probability of finding the particle at coordinate (x,t). If the momentum of the particle is $p = h\nu/v$, the group velocity of the wave-packet is v and its central wavelength is $\lambda = h/p$ (de Broglie wavelength).

Historically, this definition was suggested by the experimental evidence that particles exhibited both wave and particle nature. In the case of photons, the duality aspect was particularly striking in experiments in which the intensity of light was so low that no more than one photon at a time was crossing the diffracting apparatus, and still a diffraction pattern appeared on the detecting system. Starting with the pioneering work of Taylor(2) and later, of Dempster and Batho(3), these results were confirmed in recent times by Pfleegor and Mandel(4) and Csillag, Janossy and Haray(5). The success of the wave-particle hypothesis in other fields, such as atomic physics and spectroscopy, confirmed the validity of the duality concept, so that hardly anyone now has any doubt that the foundations of quantum theory have been laid on solid ground.

In the following, we shall subject to a critical examination the fundamental experiments of diffraction with statistically independent photons.

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We shall prove that the interpretation of these experiments took for granted that the detecting apparatus had 100 percent quantum efficiency, or that the detector could reveal each isolated photon, although this is not really so. Moreover, we shall report on an experiment of diffraction of laser photons endowed with a high degree of statistical independence and shall prove that, contrary to expectation, the diffraction pattern does not appear in this instance, even when the detection apparatus is irradiated with a number of photons certainly sufficient to produce such a pattern.

Finally, starting from the consideration that the wave-packet model of the photon is unable to justify these results, we give some arguments to believe that it should be replaced by a model of packets of photons, as suggested by other experiments, such as the famous Hanbury-Brown and Twiss(6) experiment, in which the Bose-Einstein "clumping" effect of photons was successfully detected.

2. GENERAL ANALYSIS OF THE EXPERIMENTS OF DIFFRACTION WHEN THE PHOTONS CROSS THE DIFFRACTING APPARATUS ONE AT A TIME

Implicit in any explanation of the experiments of diffraction with statistically independent photons is the assumption that each isolated photon can be revealed as a clear diffraction pattern. Each isolated photon, in other words, carries its own wave-packet which diffracts out of a pinhole, slit or double-slit, etc., and individually forms a very weak diffraction pattern, which is later reinforced by the arrival of other photons.

This assumption is not confirmed by other experiments. For instance, if one examines the available literature, one finds that photons can hardly be radiated as isolated particles from any source, because they are constantly interacting with a common radiation field(7). This implies that the photons are not emitted at random but that they have certain characteristic bunching properties(8). Moreover, if one assumes that the photons might be emitted as isolated particles, we can prove that their detection becomes then virtually impossible.

Let us consider, in fact, one of the most conventional methods of photon detection, the photographic process. It is known that the photographic grains, when exposed to light, do not become developable unless they absorb at least three or four photons within a time which can be assumed to be of the order of the coherence time of the light(9). This means that the photographic grains act as R-fold coincidence counters, where R is of the order of 3, 4 or more(10). The coherence time $\Delta\tau$, which is the inverse of the light bandwidth, in the typical case of thermal light of peak wavelength $\lambda_o = 5000Å$ and bandwidth $\Delta\nu = 10^{12}$ sec^{-1} (corresponding to $\Delta\lambda = 10Å$), is of the order of 1 psec. Photons, therefore, in order to be detected, have to be confined within a distance of the order of the coherence length $c\Delta\tau = 3 \times 10^{-2}$ cm from the target grain. As a consequence of the foregoing considerations, the assumption adopted in explaining the experiments performed with extremely low light intensity(2,3), namely that the photons were crossing the detection apparatus one at a time, was incorrect. If the probability was high that the photons were widely separated, the detection probability then became extremely small.

An assumption more in line with reality would be that, no matter what the light intensity, the photons are detected only because they are bunched and hit the target detector as a "clump". Therefore, we are dealing with packets of photons rather than packets of waves or wave-packets.

Although we have centred our argument around the photographic process of optical photon detection, we see no reason for ruling it out in the case of any other type of fast detection, photoelectric, for instance(4,5). Indeed, the fact that no photoelectric detector in the optical range has 100% quantum efficiency shows that a minimum number of photons, greater than one, is required for the release of an electron from a photoemissive surface.

At any rate, if one tried very hard and were capable of generating a beam of light whose individual photons are, as much as possible, independent, any diffraction or interference pattern would be largely destroyed. An experiment along this line has indeed been done. The intensity of a thermal light source has been greatly reduced by decreasing the number of atoms excited at the source. The photons emitted were then strongly independent. Indeed, the interference pattern was largely destroyed(11).

3. EXPERIMENT OF DIFFRACTION WITH STATISTICALLY INDEPENDENT PHOTONS FROM A LASER SOURCE

We would like now to report on an experiment of diffraction that we recently performed with statistically independent photons from a laser light source. The experimental set-up is described in Figure 1 (below). A 5 mW cw TEM_{00} mode Spectra-Physics Mod. 135 He-Ne laser was used as a source of light. The laser emitted a Gaussian beam of radius $a = 0.35$ mm at $1/e^2$ points. The peak light intensity in the central part of the beam was:

$$I_p = 2P_o/\pi a^2 = 2.59\ \mathrm{W/cm^2}\ (P_o = 5 \times 10^{-3}\ \mathrm{W})$$

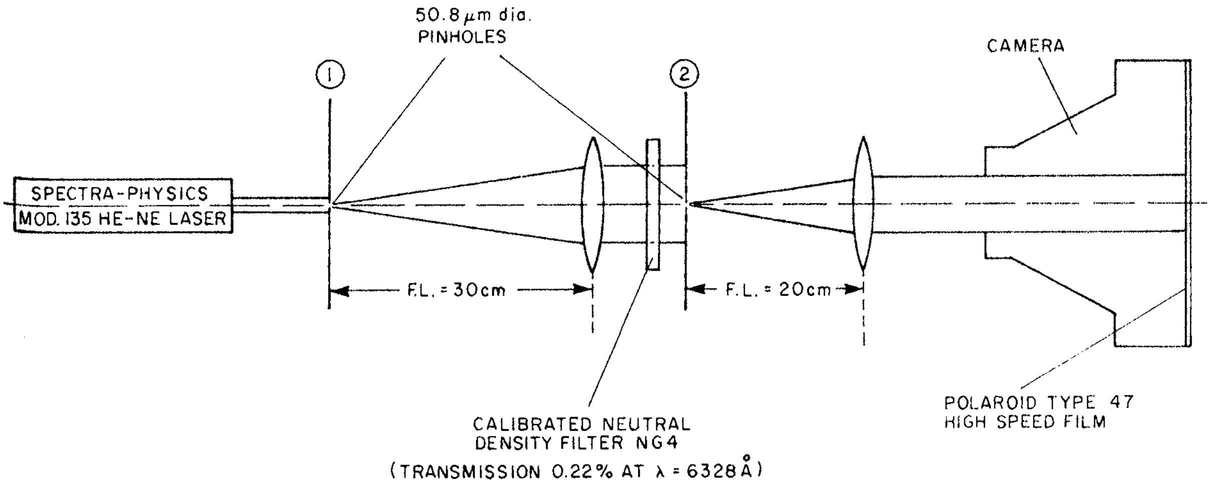

Figure 1. Experimental apparatus used to reveal the effect of the degree of statistical independence on the photon distribution on a photographic film. Without the neutral density filter along the light path, a clear diffraction pattern can be recorded on the film. With the neutral filter inserted, no diffraction pattern is recorded, even when the number of photons impinging on the film is more than two orders of magnitude larger than before.

The light intensity profile was smoothed out by means of a pinhole of diameter $d = 5.08 \times 10^{-3}$ cm positioned at the centre of the beam, at the point of maximum light intensity. The resultant emergent bright central disc of the Airy pattern was collimated by means of a simple double-convex lens located at a distance from the pinhole equal to the lens focal length $f = 30$ cm. The intensity of light at the centre of the Airy pattern resulted(12):

$$I_o = AP_o/\lambda^2 f^2 = 2.95 \times 10^{-4} \text{ W.cm}^{-2}$$

where $A = \pi d^2/4$ is the pinhole area. A second pinhole of diameter $d = 5.08 \times 10^{-3}$ was positioned at the centre of the Airy disc. The diffracted light out of this second pinhole was recollimated by means of a simple double-convex lens located at a distance from the pinhole equal to the lens focal length $f = 20$ cm. The diffraction pattern was then recorded by means of a camera equipped with Polaroid type 47 High Speed film. The intensity of light at the centre of the second Airy disc resulted in being 7.57×10^{-8} W.cm^{-2}, which meant that the number of photons crossing the second pinhole in unit time was 1.95×10^7 sec^{-1}, or that each photon was on average separated from the following one by a distance of 1.53×10^3 cm. The photons were then statistically independent and each one crossed the pinhole long before the next one did.

The objective of the experiment was the following. If the photons are statistically independent, the resultant diffraction pattern is due to the superposition of the patterns created by each individual photon or wave-packet. The separation of the photons or delay of their arrival one after the other on the photographic plate should have no bearing on the quality of the photograph and an identical number of photons reaching the film should provide identical diffraction patterns. If, on the other hand, this does not occur and the separation between photons or delay of their arrival affects the quality of the diffraction pattern, the hypothesis of independence of the photons is untenable. How can, in fact, a photon vitiate its own diffraction pattern because another photon will reach the plate more or less delayed from the first? As a consequence, if the diffraction pattern deteriorates as the separation between photons is increased, or statistical independence is approached closer and closer, then the photons cannot be considered independent wave-packets and the duality concept will run into difficulties.

Figure 2 (opposite) reports the experimental results. The first photograph (Fig. 2a) was obtained with the experimental apparatus just described. The photograph was exposed for 20 sec and 3.91×10^8 statistically independent photons produced the clearly defined diffraction pattern shown in the figure. We then inserted a calibrated neutral density filter (type NG4 — homogeneous filter — transmission 0.22% at $\lambda = 6328$ Å) along the light path (see Fig. 1). In this way, the intensity of light crossing the second pinhole was reduced by a factor of ≈ 500 and statistical photon independence was stronger than before, because only 4.29×10^4 photons were crossing the pinhole per second and each photon was separated from the following one by a distance of 6.99×10^5 cm. In order to have the same diffraction pattern as in Fig. 2a, it was calculated that an exposure time of 2h 32m was required. The first experiment performed with such exposure time failed to produce the expected result in that no light was recorded at all. Only when the exposure was increased to 17h 36m, or when 2.72×10^9 photons reached the plate (that is, a number of photons almost an order of magnitude larger than before) were we able to detect some light (see Fig. 2b). Finally, when the exposure time was pushed to over two weeks (more exactly 336h 20m, or 5.19×10^{10} photons on the plate), the resultant photograph was better defined, although the expected diffraction pattern did not appear, as Fig. 2c shows.

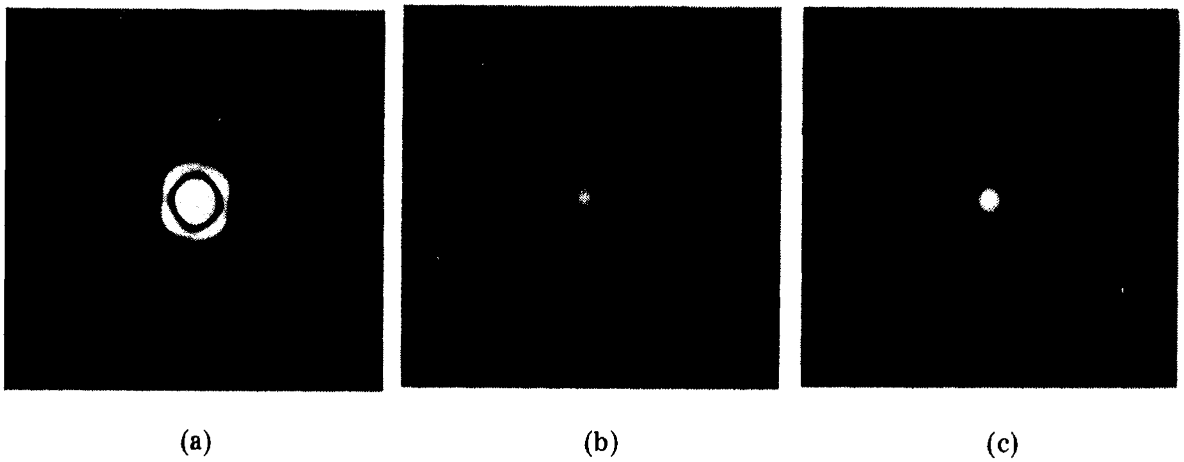

Figure 2. (a) Regular diffraction pattern obtained with 3.91×10^8 statistically independent photons reaching the photographic film (20 sec exposure time). (b) Picture obtained when 2.72×10^9 photons reach the photographic film (17h 36m exposure time). (c) Picture obtained when 5.19×10^{10} photons reach the photographic film (336h 20m exposure time). The (b) and (c) pictures show that a diffraction pattern is missing, although the number of photons impinging on the film is ≈ 1 order of magnitude, or over two orders of magnitude, respectively, larger than that which was capable of producing a clear diffraction pattern in (a).

4. ANALYSIS

If we disregard the hypothesis that the photons carry their own wave packet and re-examine the experiment in light of the considerations expressed in Section 2 above, we would be able to justify qualitatively the foregoing results as follows. Firstly, knowing that the photographic grains cannot become developable unless they absorb at least three or four photons within the coherence time of the light, each spot appearing on the photographic plate is the result of the absorption of such a number of photons. Secondly, if light is intrinsically made up of aggregates or clumps of photons, these clumps in the first experiment of Fig. 2a do not find any obstacle along the optical axis of the apparatus and cross unimpeded the two consecutive pinholes. The number of photons making up each aggregate must necessarily be large. On crossing the pinhole, the photons in the clumps are able to evolve into smaller packets of 3 or 4 photons each, or more, which can then be detected by the photographic film in the form of a regular diffraction pattern. The photograph of Fig. 2a shows that 20 sec is a sufficient exposure time for such a clear pattern. By contrast, when the strong neutral density filter is inserted along the light path, and the light intensity is consequently reduced by a factor of ≈500, most of the clumps crossing the second pinhole are now composed of a number of photons which is reduced by the same factor. They, in turn, diffracting out of the pinhole, evolve into several packets made up of less than 3 or 4 photons, which therefore cannot be detected. If, however, one allows a longer exposure time to compensate for the loss of photons which cannot be detected, the chance of having some larger clumps is increased. Fig. 2b and 2c, which have been exposed for 17h 36m and 336h 20m, respectively, indicate that this is what happens. The diffraction pattern is still not present in these pictures, but it is conceivable that, on pushing the irradiation to times of the order of months, the pattern might reappear. We have not pushed the irradiation to such excessive time.

In conclusion the experimental results reported in the previous section are better explained, at least qualitatively, if a model of packets of photons, rather than a wave-packet model, is assumed. In the next section we will discuss further the physical reality of such a model.

5. DISCUSSION

In order to have a better understanding of the physical reality of the model of packets of photons introduced here, we shall contrast it with the wave-packet model and shall find that the two models yield conflicting predictions of the outcome of diffraction experiments.

First, let us see what the wave-packet model predicts. This model predicts that the diffraction of photons from a slit or pinhole is the result of the superposition of the diffraction of each independent wave-packet or photon and that the build-up or clarity of a diffraction pattern on a photographic plate proceeds linearly with the number of photons reaching the plate.

By contrast, the model of packet of photons predicts that the photons are not independent but that they tend to arrange themselves in a conglomerate of points. These conglomerates or clumps do not have an equal number of photons. Some of them are composed of only a small number of photons which, on crossing a slit or pinhole, evolve into packets of less than 3 or 4 photons, which cannot be detected because optical detectors do not respond to irradiation below a critical number of photons. As a consequence of such impossibility of recording all photons reaching the detector, the build-up or clarity of the diffraction pattern cannot proceed linearly with the number of photons. In conclusion, the two models predict different results and we have seen that the experimental results reported in Section 3 above tend to confirm the hypothesis that light is made up of packets of photons.

Finally, the remaining questions as to the mechanism of formation of these packets of photons and how they evolve into a diffraction pattern will be thoroughly answered in a separate article, to be submitted soon for publication(13).

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9. In general, more than this number will be required since not all the photoelectrons which are produced make a contribution to the latent image formation (Rosenblum, W.M., *J. Opt. Soc. Am.*, 58, 60 (1968); Dainty, J.C. and Shaw, R., *Image Science*, Academic Press, London, p.34 (1974); Kowaliski, P., *Applied Photographic Theory*, John Wiley & Sons, p.320 (1972).)
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