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INTERFERENCE EXPERIMENTS WITH STATISTICALLY INDEPENDENT PROTONS

Yu. P. DONTSOV and A. I. BAZ'

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The statistics of monochromatic photons impinging on the cathode of an image converter is investigated. The visibility of the interference pattern was lessened considerably when a weak beam of statistically independent photons passed through a Fabry-Perot interferometer.

1. INTRODUCTION

AT the beginning of the twentieth century, when the photon theory of light was revived and quantum mechanics was evolving, the interference properties of an individual photon became a subject of inquiry that has continued to have timely importance up to the present day.

The interference properties of individual photons were first studied experimentally by G. J. Taylor in 1909;[1] more thorough experiments were performed much later by Dempster and Batho.[2] These investigations showed that the interference pattern obtained when a very low photon density is photographed during a long exposure time ($t_{\text{exp}} \approx 24$ hours) is practically the same as that obtained with high light intensity. In the 1930's S. I. Vavilov obtained similar results visually.[3] Much more recently Jánossy and Naray[4] used a photomultiplier as a photon counter to investigate the interference pattern produced by a light flux $\approx 10^8$ photons/sec. A large difference was observed between the interference patterns obtained with high and low light intensities. We believe, however, that this difference lies within the limits of the experimental errors.

The earlier experiments of Taylor, Dempster and Batho, and Vavilov, where individual photons were not registered, are not very convincing when examined more carefully. The work of Jánossy and Naray, who did register individual photons, represented a higher level of investigation. However, in our opinion certain shortcomings existed there in connection with the relatively large dark current of the photomultiplier: The signal-to-noise ratio was quite low ($\approx 1:1$), the photon density in the beam was relatively high (≈ 18 photons/sec) and there was evidently a fairly high density of excited atoms in the light source.

The last of these circumstances is all the more important because it has now been established reliably that the photons in light beams are correlated to a considerable degree and cannot be considered statistically independent as a rule. This means in quantum-theoretical language that the probability $P(x_1t_1; x_2t_2)$ of registering two photons at two different points of space-time does not, as a rule, equal the product $P_1(x_1t_1)P_2(x_2t_2)$, where $P(x_it_i)$ is the probability of registering a single photon at the point (x_it_i). Indeed, this same effect exists in the classical theory, although the latter theory is concerned not with the registration of photons but with the probability of observing certain values of the electric (and magnetic) field at the points (x_it_i).

In western literature this property of radiation fields has been called the "bunching effect," which has a double origin. First, the emission from a

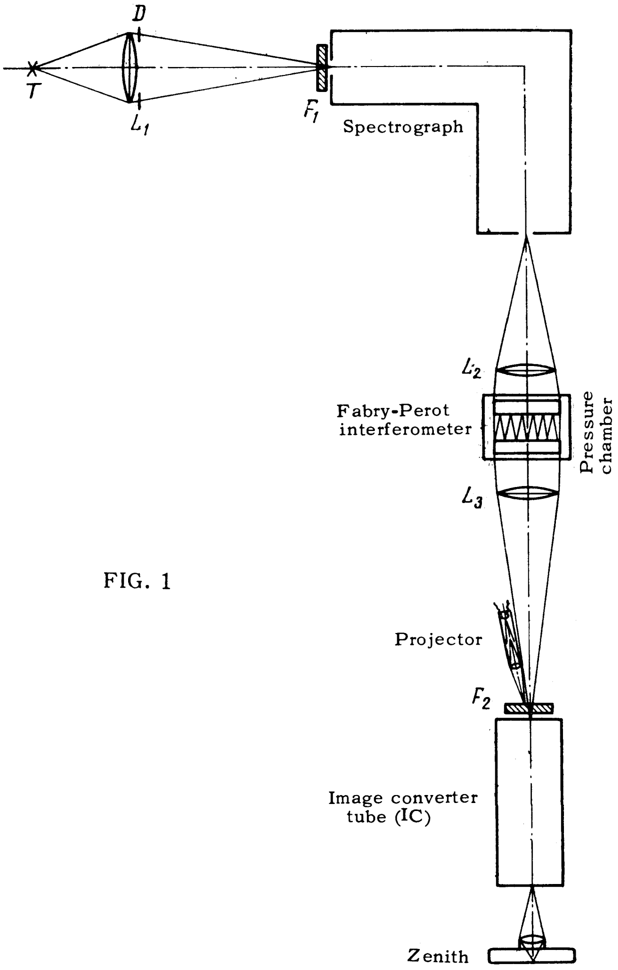

FIG. 1

gaseous source may consist of correlated photons. This effect, which results from the radiative coupling of individual atoms, was pointed out by Dicke in 1954.[5] Secondly, radiation in free space can become "autocorrelated."[6] An experimental confirmation that correlation exists between photons in light beams was first obtained by Twiss and Hanbury Brown in 1956,[7] whose experiment was subsequently repeated with no substantial modifications by several investigators.[8-12]

It was the aim of our present experiment to investigate the interference properties of weak light beams consisting of statistically independent photons, and to answer the basic question: Will a large number of individual photons passing through an interferometer produce an interference pattern?

Our photon detector was able to register single photons. If we register ~ 20 photons/sec the signal-to-noise ratio is $\gtrsim 20:1$. Thus the present work repeats the aforementioned experiments to a considerable extent, but with a more highly perfected technique.

2. EXPERIMENT

The experimental setup is shown in Fig. 1. The light source was an electrodeless discharge tube filled with 20 mg of 99.99% pure Hg^{198} and spectrally pure argon to a pressure ≈ 4 mm Hg. The discharge was initiated by a high-frequency (≈ 10 Mc) field. The image of the source was projected by the objective lens L_1 (equipped with a variable diaphragm D) on the slit of an ISP-51 spectrograph, which functioned as a monochromator for the 407- and 405 mμ mercury lines used in our experiments. After passing through the exit slit of the spectrograph the radiation was focused in a parallel beam, by means of the lens L_2, on a Fabry-Perot interferometer (FP) with a 30-mm separation between the reflecting surfaces. The interferometer was placed in a pressure chamber in which the temperature was maintained constant to within 0.1°C. The interference pattern was projected by the objective lens L_3 on the antimony-cesium photocathode of an image converter tube (IC); the image on the output screen of the latter was photographed. The two operating modes of the IC were to register each photoelectron in the case of high gain, and to sum the action of a few photoelectrons on photographic film with lower gain. The photon registration efficiency was about 10%. When we cooled the photocathode to a temperature between $-50°$ and $-60°$C the IC dark current was at most 1.2 electrons per second on the screen area (0.4×5 mm^2) that was occupied by the image of the spectrograph exit slit. To test the influence of IC operating instability on the quality of the interference pattern when a low photon density was used, a parallel-bar resolution test target, with line separations from 0.05 to 0.3 mm, was projected on the IC cathode. The projector M used for this purpose followed the interferometer, and the photon density impinging on each bar of the test target was of the same order as that reaching the IC screen from the FP. Thus the quality of the test target image indicated how the IC was functioning during each exposure.

3. EXPERIMENTAL RESULTS

It will be seen subsequently that our source provided a stream of highly intercorrelated photons. Even at the lowest light intensities (about 100 photons/sec on the IC photocathode) that were attainable by means of the diaphragm a distinct interference pattern was observed on the IC output screen. The degree of contrast of the pattern (the ratio between the photon densities of the interference maxima and minima) was practically independent of the flux.

In order to minimize the correlation between photons in the beam and thus obtain a stream of isolated, statistically independent, photons we used two procedures. In the first of these the density of

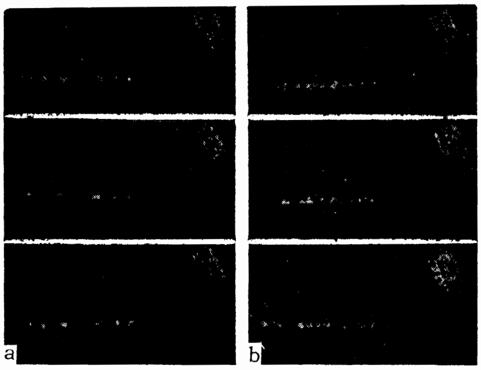

FIG. 2

excited atoms of the source emitting the 407 mμ line was reduced by decreasing the discharge tube current to $N_a \leqslant 10^2$ atoms/cm^3. In the second procedure the light beam from the source was passed through a gray absorbing filter F_1 preceding the interferometer. We used filters having 10^2—10^5 attenuation factors.

The beam of statistically independent photons produced by either method passed through the interferometer without producing an interference pattern. This result was confirmed by several series of experiments. In one series the IC output pattern was photographed with a 15-sec exposure time so that ~ 400 photons were registered in each frame. Typical examples of these 15-sec exposures are shown in Fig. 2, where the right-hand photographs were obtained with the filter F_1 (with a 10^2 factor) from $N_a \geqslant 10^5$ atoms/cm^3 in the source, and the left-hand photographs were produced by the same source density without use of the filter. In the latter case the beam was reduced by the diaphragm D (of 0.3-mm diameter) so that an identical photon flux reached the IC in each instance. The left-hand frames show the interference pattern clearly. Practically no photons reached the central region, where the central minimum of intensity was expected from the experimental arrangement. In the right-hand frames the photons are distributed more uniformly over the entire area and appear where we would expect to find the central minimum. In each photograph we observe the image of the bar resolution test target registered as a control simultaneously with the experimental pattern. The good quality of this image indicates stable functioning of the IC in all the experimental stages.

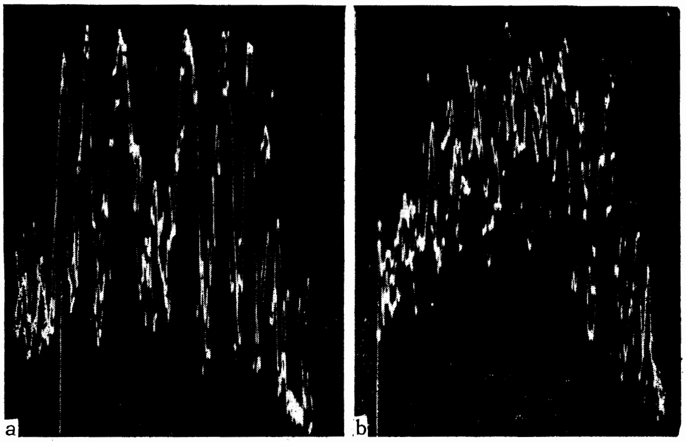

FIG 3

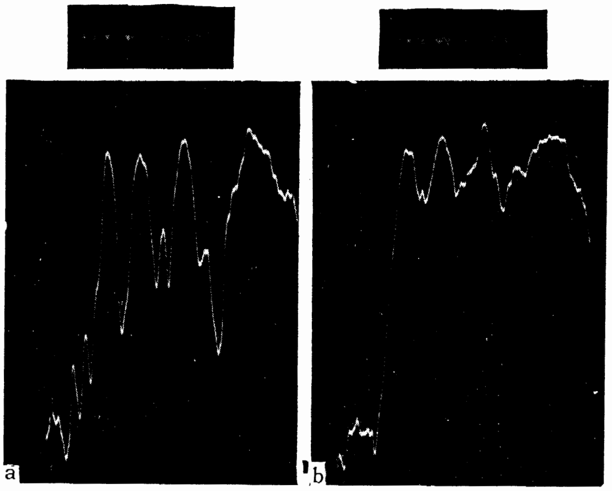

FIG 4

Figure 3 shows the results obtained from photometric measurements of the respective photographs.

In the second experimental series, obtained with one-minute exposures, the average number of registered photons was ≈ 1500. Figure 4a shows one of the comparison frames obtained with a type NS gray filter (with a 10^2 factor) following the interferometer in position F_2; Fig. 4b was obtained with the same filter preceding the interferometer in position F_1. The corresponding microphotograms are shown in the lower portions of these photographs. A comparison of these two patterns shows clearly the marked impairment of the interference pattern (in Fig. 4b) that results when statistically independent photons impinge on the interferometer.

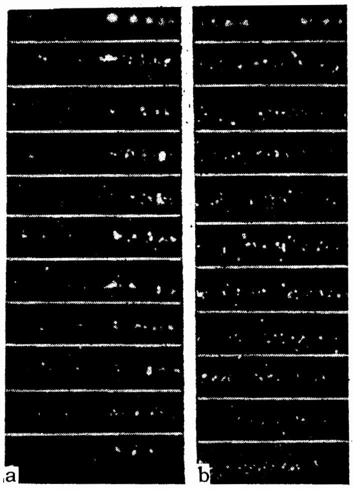

FIG 5

It should be noted that the background surrounding a line is stronger in the comparison photograph.

In the third series 150 one-second-exposure photographs of the IC screen were obtained. The average number of registered photons varied from 20 to 30; several examples are shown in Fig. 5. In the left-hand frames the photon flux had been attenuated by the diaphragm with ~0.3-mm diameter; in the right-hand frames the photon beam had been attenuated 100 times by a filter in position F_1. In the latter photographs the photons are distributed practically uniformly over the entire area of the spectral line image. The uppermost comparison frames in each column were obtained with no filter or diaphragm in $1/_{100}$-sec exposures using somewhat higher light intensities.

In our study of these photographs we plotted the correlation functions for the photon distributions on the IC screen. The condition for interference is

$$k\lambda = 2t\cos\varphi_k \approx 2t(1 - \varphi_k^2/2).$$

Here k is the interference order, λ is the wavelength of the light, t is the separation of the reflecting mirrors, and φ is the light incidence angle on the interferometer. The corresponding density $N(\varphi^2)$ of spots on the IC screen should exhibit maxima at the points

$$\varphi_k^2 = \frac{\lambda}{t}\left(k - \frac{2t}{\lambda}\right).$$

Therefore the correlation function $P(y_l)$, defined by

$$P(y_l) = \sum_k \{N(\varphi_k^2) - \bar{N}\}\{N(\varphi_k^2 - y_l) - \bar{N}\},$$

averaged over the entire area of the image (with N representing the density of the spot image) will be a periodic function of y and its period will equal the region of free dispersion of the interferometer. In the absence of interference P(y) will be a rapidly declining function of y.

Figure 6 shows the correlation functions P(y) obtained by averaging over several frames; the curves in Fig. 6, a and b. were obtained for cases where the interferometer received beams of statistically independent photons produced by methods 1 and 2, respectively; the curve in Fig. 6c pertains to the case of correlated photons (derived from a high source density of excited atoms, using filter F_2). In the last case we observe alternating maxima indicating the existence of a clear interference pattern. On the other hand, the curves in Fig. 6, a and b, have no periodic structure; this proves that independent photons produce no interference pattern.

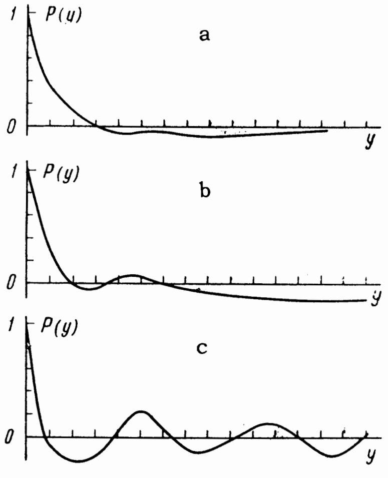

FIG. 6

We shall now discuss how we determined the existence of photon correlation in a beam. Our basis was the fact that when a beam of statistically independent photons impinges on the IC cathode and comprises only the insignificant load of ~200 photons/sec that was maintained in our experiments, the photoelectron flashes on the IC output screen should exhibit a Poisson distribution. We were considering (a) the photon distribution over different interference maxima, and (b) the distribution Q(N) of the number of photons registered by the IC per unit of time.

When our experimental photons were emitted by excited atoms of not too low density ($N_a \gtrsim 10^5$ atoms/cm^3) and no filter was used, we obtained the results that will now be presented.

The probability that with a given average number of flashes belonging to one interference maximum (i.e., order) no flash will pertain to one, two, three etc. orders differs strongly from the theoretical probabilities derived for a random distribution of the flashes. Table I gives the results of two series. The first line gives the number of orders that were not represented by even a single photon. The remaining lines give the experimental and theoretical probabilities that some orders will be missing. The probability that the experimental distribution of probabilities resulted from random fluctuations is below 10^{-6}. It thus seems as though $\bar{n}$ (the mean number of events in the Poisson distribution) was smaller than the average number of photoelectron flashes included in a single interference order. It is therefore reasonable to assume the correlated emission of photoelectron

Table 1

Number of missing orders	1	2	3	4
Poisson probability ($\bar{n} = 18$ flashes/sec)	0,64	0,16	0,02	
Experimental probability	0,70	0,30	0,10	
Poisson probability ($\bar{n} = 28$ flashes/sec	0,22	0,02	$1.7\cdot10^{-3}$	$5\cdot10^{-5}$
Experimental probability	0,50	0,38	0,16	0,12

Table 2

Number of frames in series	93	15	30	15	15	30
$\bar{n}$	17	15	21	25	13	26
D	9	5	6	15	4	10
$D/\bar{n}$	0.5	0.3	0.3	0.6	0.3	0.4

groups, so that the impinging beams contained "bunches" of correlated photons.

The dispersion D of the numbers of flashes registered in photographic series with one-second exposures is much smaller than $\bar{n}$, the average number of flashes. In Table II the first line gives the number of photographs in a series; the second, third, and fourth lines give the values of $\bar{n}$, D, and $D/\bar{n}$ for the corresponding series.

Whenever the density of excited source atoms was reduced to $N_a \leqslant 10^2$ atoms/sec or we used a filter, the ratio $D/\bar{n}$ was close to unity (see Table III). This indicated that we were registering streams of individual, statistically independent, photons.

As already mentioned, in the case of statistically independent photons the statistics of the flashes must be of the Poisson type. The very fact that D was smaller, not larger, than $\bar{n}$ can evidently be accounted for only by a reduction of the quantum yield (through fatigue) of the IC photocathode when the number of simultaneously incident photons increases.[13] In view of the small average density of our experimental density the described effect could only occur if bunches of correlated photons struck the photocathode.

Although we cannot consider that our present experimental work yielded finally determinate results, even the first experiments obviously prove that the following effects occur:

1. The photons emitted by an ordinary light source (and specifically a mercury vapor tube) are highly intercorrelated. Their correlation is probably manifested by the emission of photons in "bunches."

2. Photon correlation disappears either when the density of excited source atoms is small, or when the photon beam traverses a sufficiently dense gray absorbing filter.

3. A beam of statistically independent photons passing through a Fabry-Perot interferometer with 30-mm mirror separation does not form an interference pattern; the photons are distributed practically uniformly at the locations of interference maxima and minima. The disappearance of interference cannot be accounted for by such a trivial hypothesis that our experimental filter was of poor quality and thus broadened the spectral lines. Nevertheless, the latter possibility was investigated. Light from a He-Ne laser, which emitted a very dense stream of strictly correlated photons was passed through the same filter placed 45 cm ahead of the Fabry-Perot interferometer. The interference pattern was not affected, thus proving that the filter causes practically no distortion of the spectral distribution in a line.

Table 3

$N_a \lesssim 10^2$ at/cm^2				$N_a \gtrsim 10^5$ at./cm using filter	
Number of frames in series	30	15	15	30	30
$\bar{n}$	13	16	22	24	24
D	10	17	18	24	21
$D/\bar{n}$	0,8	1,0	0,8	1,0	0,9

The presence of correlated photon "bunches is not especially surprising. However, the actual nature of the effect (the disappearance of the interference) which is the main result of our work is still not clearly understood and is being investigated further at the present time.

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1