Quantum optics experiment on the test of empty wave hypothesis

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Abstract

The experiment measured the absorption of single photons by absorbers with various absorption coefficients, in one of the beams, after the photons interacted with the beam splitter. The measurements showed that the absorption corresponds to single photon traveling in either one or another beam. The measurements support the original empty wave hypothesis which has been advanced in a number of works.

Key words: single photon experiment, subquantum processes, empty wave, de Broglie-Bohm theory

Introduction

In 1986 Grangier, Roger and Aspect [1] have demonstrated the interference of the two output beams from the beam splitter in experiments using single photon states, even though the photon can only be detected in one of the two output beams for a given run of the experiment. Paper [2] considers the hypothesis that one of the beams contains a wave which is not accompanied by a particle, i.e. an empty wave. A number of works suggest

experiments for the detection of empty waves (see, e.g. [3-5]); however, until now no experimental evidence of the existence of such a wave has been received.

The Born rule connects the wave function to the probability density of finding the particle at a given point. However, this rule is not a basic law. In de Broglie-Bohm theory the wave is considered a physical reality, and the link between the probability density and the wave function has the status of a hypothesis. This means that the wave function may be not equal to zero even in the part of space where the particle is not observed. Hence, an empty wave may also be described by the wave function, which may explain the interference of the wave containing the photon, i.e. the probability wave or full wave, and the empty wave. In paper [2] some assumptions are made which are true in the de Broglie-Bohm model.

Clearly, in order to discuss the empty wave hypothesis it is important to understand the physical meaning of the wave function, i.e. to have an adequate interpretation of the wave function. We will not discuss various interpretations of wave function here. The fact that so many exist testifies to the absence of a satisfactory one. This is why many physicists lean towards the instrumentalist interpretation, best summed up in the succinct slogan "Shut up and calculate!" [6].

Like many physicists, we are uncomfortable with any of the commonly known interpretations. In our view, for a particle to be found in a point in space, it must actually be there at the moment when it is found. It is clear that for a particle to be manifested at a point in space, physical processes are needed to provide for this manifestation. In the early 1960ies, de Broglie formulated an approach adding a chance element to the movement of a particle; this chance element is caused by the particle's interaction with the hidden "subquantum environment". In papers [7,8] we offer an interpretation of the wave function in which wave function is a consequence of processes taking place at the level of the organization of matter which underlies the phenomena described by quantum mechanics. We use the term "subquantum processes" for these processes. We think that

the road into the structure of matter is a staircase with an infinite number of steps, and the subquantum level is one of these steps.

Experiments observe the manifestation of the particle in a certain point of the probability wave. It is common knowledge that behind every chance there is a rule. We do not know the rules of the subquantum world determining the formation of wave trains in which the particle manifests as an observable object. It is clear, however, that the photon can manifest anywhere in the wave train, and that this possibility is determined by some subquantum processes. A direct proof of the existence of an empty wave would mean that along with the wave train where the photon manifests, there also exists a wave train containing the potential possibility of the photon manifestation, but the actual photon does not manifest, and thus cannot be detected. Note that at any given time the photon manifests only in one of the points of the probability wave train. In all other points at that moment the wave may be considered empty.

According to [1], after the recombination of two beams an interference picture is observed. This implies that two coherent wave trains appear as a result of the interaction of the photon with the beam splitter. If the photon were to manifest in both wave trains, it would mean that its wave function is the superposition of two probability waves: the transmitted one and the reflected one. Note, that the photon can only be detected in one of the two output beams. The empty wave hypothesis is consistent with the suggestion that the photon manifests in only one of the two output beams. In this case the photon's wave function cannot be a superposition of two probability waves. Thus, experiments are needed which will clarify whether the photon wave function after the interaction with the beam splitter is the superposition of two probability waves or the superposition of a probability wave and an empty wave.

Experiment and discussion

Our experiment is illustrated in figure 1.

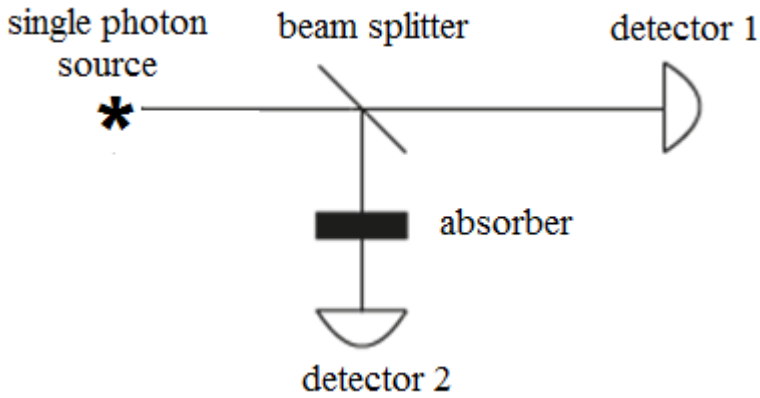single photon source   beam splitter   detector 1

absorber

detector 2

Fig.1

Let us consider that after the beamsplitter the wave function of the single photon is the superposition of the wave functions corresponding to the transmitted and the reflected waves:

$$\psi = c_1 \psi_{tr} + c_2 \psi_{re} \qquad (1)$$

where the ratio of $|c_1|^2$ and $|c_2|^2$ is equal to the ratio of the numbers of photons registered by the detectors 1 and 2 in the absence of the absorber. Let N_0 is the number of the photons registered by both detectors in the absence of the absorber. Then numbers of the photons registered by the detector 1 and by the detector 2 will be equal to $N_0|c_1|^2$ and $N_0|c_2|^2$ accordingly.

If the wave function of the single photon is the superposition of the wave functions and the absorber does not influence unabsorbed photons, then the ratio of the numbers of the photons registered by the detectors 1 and 2 will be equal to the ratio of $|c_1|^2$ and $|c_2|^2$ regardless of the presence of the absorber, <u>since the detectors count only unabsorbed photons (we recall that, in the case of the superposition, the absorption of the single photon means that its existence ceases in both beams).</u> Let N_{ab} is the number of the absorbed photons. If the wave function of the single photon is the superposition (1) and the absorber does not influence unabsorbed photons, then at the presence of the absorber the numbers of the photons registered by the detector 1 and by the detector 2 will be equal

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to $(N_0 - N_{ab})|c_1|^2$ and to $(N_0 - N_{ab})|c_2|^2$. The numbers of the photons registered by the detectors 1 and 2 will diminish on $N_{ab}|c_1|^2$ and $N_{ab}|c_2|^2$ accordingly.

The measurement results are provided in Table 1.

k	T	N_1	N_2	N_1/N_2	$(N_1/N_2)_{av}$
0	2	44730	33745	1.325	
0	0.02	459	343	1.339	1.346
0	0.002	45	33	1.373	
0.1	2	44271	26068	1.698	
0.1	0.02	433	255	1.696	1.701
0.1	0.002	43	25	1.710	
0.2	2	44188	20502	2.155	
0.2	0.02	446	210.6	2.118	2.096
0.2	0.002	44	28	2.016	

Table 1. Column names:

k - absorption coefficient of the absorber

T = 20 T_m

T_m - duration of one measurement cycle

N_1 - average number of photons registered by detector 1 in one measurement cycle

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N_2 - average number of photons registered by detector 2 in one measurement cycle

$(N_1/N_2)_{av}$ - average ratio of the number of photons registered by the detector 1 and the detector 2 at different T

The table 1 shows that the ratio of the number of the photons registered by the detector 1 and the detector 2 without the absorber is 1.346 (with variation in the third decimal at various values of T). This means, that in the absence of the absorber the number of the photons registered by the detector 1 is

$$(N_1)_0 = 0.574 N_0 \tag{2}$$

and the number of the photons registered by the detector 2 is

$$(N_2)_0 = 0.426 N_0 \tag{3}$$

Let us suppose that after the beamsplitter the wave function of the single photon is the superposition

$$\psi = c_1 \psi_{tr} + c_2 \psi_{re} \tag{4}$$

$$|c_1|^2 + |c_2|^2 = 1$$

where $|c_1|^2 = 0.574$, $|c_2|^2 = 0.426$.

Let us admit that the absorber does not influence unabsorbed photon and the photon wave function remains the superposition (4). Then, when absorber is present, the number of the photons registered by the detector 1 will be equal to $0.574(N_0 - N_{ab})$ and the number of the photons registered by the detector 2 will be equal to $0.426(N_0 - N_{ab})$. The ratio of the numbers of the photons registered by the detectors 1 and 2 will remain equal to the ratio 0.574 and 0.426, i.e. equal to 1.346. Our measurements have shown, however, that the presence of the absorber in the path of the reflected beam does not change the number of the photons registered by the detector 1. In the presence of the absorber, the number of unabsorbed photons recorded by the detector 2 corresponds up to the third decimal to the expression

$$N_2 = (N_2)_0 10^{-k} \tag{5}$$

Because the presence of the absorber does not change the number of the photons recorded by the detector 1, the number of absorbed photons is equal to

$$N_{ab} = (N_2)_0 - N_2 = (N_2)_0 \left(1 - 10^{-k}\right) = 0.426 N_0 (1 - 10^{-k}) \tag{6}$$

In the presence of the absorbers the ratio of the numbers of photons registered by the detectors 1 and 2 also up to the third decimal corresponds to the expression

$$\frac{N_1}{(N_2)_0 10^{-k}} = 1.346 * 10^k \tag{7}$$

so it does change.

Let us suppose, that the absorber influences unabsorbed photon, and as a result the photon appears in the reflected beam (like an electron appears under influence of light in two slits experiments [9]). This photon will be registered by the detector 2. Obviously, it must increase the number of the photons registered by the detector 2 and, accordingly, must decrease the number of the photons registered by the detector 1 (but not to increase this number and to do it equal to $N_0 |c_1|^2$). However, in our experiment formulas (2) and (5) describe the numbers of photons, registered by the detectors 1 and 2 without any amendments that could be a result of absorber influencing unabsorbed photons.

Let us suppose now. that the photon appears in the reflected or transmitted beam as a result of some influence after the beamsplitter. In this case the photon wave function will not be the superposition of the wave functions corresponding to the transmitted and the reflected waves. However, we did not find in our experiment a possible source of such a violation of the superposition of the photon wave function.

The results of our measurements correspond to the photon traveling in either one or another beam. This means that the photon's wave function after the interaction with the beam splitter is not the superposition of two probability waves. At the same time, for the interference in the experiments [1] to be observed, two waves must be superposed. This means that while the photon is traveling through one beam, the empty wave is traveling through the other beam. In other words, the wave function of the photon after the interaction with the beam splitter is the superposition of the probability wave (full wave) and the empty wave.

Conclusion

The results of our measurements and of experiment [1], combined together, demonstrate the existence of the empty wave. Quantum mechanics is a fundamental theory which allows to describe a vast number of physical phenomena. However, as a truly fundamental theory, it cannot explain and describe itself. Accordingly, quantum mechanics says nothing about subquantum processes which provide for the existence of the empty wave.

The survey "Models of wave-function collapse, underlying theories, and experimental tests" [10] points out: "Quantum mechanics is an extremely successful theory… One should of course stay cautioned against assuming that quantum theory will be successful through and through … The fact that a theory is extremely successful in one part of the parameter space should not be taken as a guarantee that it will continue to be successful in a different part of the parameter space … And there are historical examples of long-standing successful theories eventually turning into approximations to more general theories when their extrapolation into a new part of the parameter space failed to be confirmed by experiment."

The need to confirm our results and to accomplish further experiments is obvious. Experimental proof of the existence of the empty wave may be useful in developing a more general theory, to which quantum mechanics will be an approximation.

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