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THE DOUBLE SLIT INTERFERENCE OF THE PHOTON-SOLITONS

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Abstract. It is shown that a solitary quantum system (photon, electron) when passing through two open slits could interfere because of the real de Broglie's wave which "guide" the particle to well-defined directions. A comparison between classical waves and particle waves can show the essential differences in the interpretations of interference phenomenon of the particles known up to now. New experiments are proposed which could distinguish between the classical electromagnetic waves and the photon-solitons. These experiments are simple, effective and decisive because they can change our understanding of nature.

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1 Introduction

We continue to search new experiments, which can distinguish the photon-soliton from a classical electromagnetic wave [1,2] and in this way either to disapprove or confirm the reality of our solitons [1]. We understand that if a great number of experimental facts does not contradict our model of solitons as shown in [1,2], it is not a prove for such solitons that they are real, and our confidence in this model grows. If only one experimental fact contradicts with the solitons [1], this model should be refuted.

As shown in [1] the electromagnetic field of a single photon must be concentrated in a very small volume. The relation between the soliton electric field E_0 and the photon frequency ω is $E_0^2 = \dfrac{8m_0\hbar\omega^3}{e^2}$, where ω is the frequency obtained from the interference phenomenon, i. e. de Broglie's frequency; m_0 and *e* are the mass and the electric charge of electron, respectively. The energy of the photon $\hbar\omega = E_0^2 V$ and $V = \dfrac{e^2}{8m_0\hbar\omega^2}$, the effective length l_e of the electromagnetic field of the soliton and the wavelength λ of de Broglie are related: $l_e = \lambda/4\pi$. Therefore, the electromagnetic field occupies only a small part of A and a very small part of the photon wave package. These results can be used for experimental checks of our model [1,2].

Now it is accepted that the interference on the two slits of the classical waves and the particles differs only in the interpretation of the absolute value of the square of the amplitude [3]. For the classical waves (sound wave, wave of the surface of a liquid, electromagnetic wave and other waves) the square of the amplitude is proportional to the energy (intensities) of the waves. When such waves interfere the intensity (energy) of the initial wave (after interference) is redistributed in different directions; in some of the directions the energy can be zero and in others — the energy can be many times greater than the initial energy of the wave (before interference).

In quantum physics (interference of the particles) it is accepted that the square of amplitude is proportional to the probability to find a particle in some direction (to the number of monochromatic particles). In some directions, the number of particles can be zero (after interference); in other directions, this number must be many times greater (redistribution of the number of particles).

Here, we would examine the double slits interference of the photon-solitons and show that the number of photon-solitons cannot be proportional to the square of the amplitude. This conclusion is true for every particle (electrons, neutrons, photons). We propose a new interpretation of the number of particles and some new experiments, which could distinguish between the classical electromagnetic waves and photon-soliton. For this purpose, it is necessary to remember in brief, the classical wave interference.

2 Classical Waves Interference

In Figure 1 an experimental setup for successive observation of the double slit interference of a classical wave (sound wave) is shown. The distance r_1 between two barriers (marked with 1 an 2) is equal to the distance r_2 between the barrier (2) and the detector D (which can register the intensity of the sound wave). The generator (source) of the sound wave is marked with S. When one of the slits (on the barrier 1) is closed, the initial amplitude on the barrier 2 is A_0. The distance between the two slits in the barriers is $d = 2a = 2\lambda$ (λ is the wavelength of sound). The two stages of the interference are completely identical and symmetrical $r_1 = r_2 = r$.

The amplitude $A_1(r, \Theta_1))$ after the barrier (1) is

$$A_1(r,\theta_1) = 2A_0(r,\theta_1)\cos\Big(\frac{2\pi a}{\lambda}\sin\theta_1\Big). \tag{1}$$

After the second barrier (2) (when $\theta_1 = 0$) the amplitude $A_2(r,\theta_2)$ will be

$$A_2(r,\theta_2) = 2A_1(r,\theta_1)\cos\Big(\frac{2\pi a}{\lambda}\sin\theta_2\Big).$$

Alternatively, which is the same

$$A_2(r,\theta_2) = 4A_0(r,\theta_1)\cos\Big(\frac{2\pi a}{\lambda}\sin\theta_2\Big). \tag{2}$$

It is known that for each classical wave the square of the amplitude in some direction ($\theta_0 \pm d\theta$) is proportional to the intensity (energy) of the wave in this direction. The

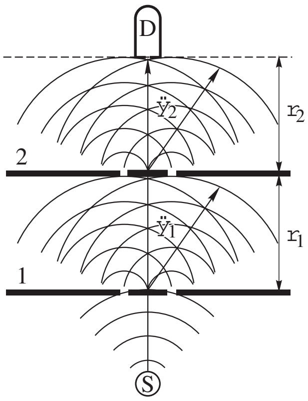

Fig. 1. Two stages double slit interference of a classical (sound) wave In consecutive way: generator S, two barriers *1, 2* and the detector D. The interference of waves with different modulus of amplitudes is established.

square of the amplitudes (1) and (2) is

$$|A_1(r,\theta_1)|^2 = 4|A_0(r,\theta_1)|2\cos^2\Big(\frac{2\pi a}{\lambda}\sin\theta_1\Big), \tag{3}$$

$$|A_2(r,\theta_2)|^2 = 16|A_0(r,\theta_1)|2\cos^2\Big(\frac{2\pi a}{\lambda}\sin\theta_2\Big). \tag{4}$$

For our classical (sound) waves the intensities (energies) J are proportional to the corresponding square of amplitudes (3), (4):

$$J_1 \sim |A_1(r,\theta_1)|^2, \qquad J_2 \sim |A_2(r,\theta_2)|^2. \tag{5}$$

For further investigations, remember that in our simple experiments $d = 2\lambda$ and the square of amplitudes (3) and (4) has the maximums at $\theta_1 = \theta_2 = \theta$. The directions of these maximums correspond to θ equal to $0°$ and $\pm 30°$. In the other directions the square of amplitudes is smaller or equal to zero. One can find the ratio of energies (5) (for example at direction $\theta = 0$)

$$\frac{J_1}{J_2} = \frac{4|A_0(r,\theta_1)|^2}{16|A_0(r,\theta_1)|^2} = \frac{1}{4}. \tag{6}$$

The same ratio of energies (intensities) is obtained for two other directions ($\theta = \pm 30°$). So, when only barrier 1 exists, the energy in the direction $\theta_1 = 0$ is J_1 and when one uses the two barriers the energy which could be registered by the detector D is $J_2 = 4J_1$. The conclusion is that this simple experiment can be used for amplification of the sound (classical) wave energy (in some directions).

3 Interference in Quantum Physics (Interference of Particles)

As is known in quantum physics the interference of particles is based on the theory, which is mentioned above. Because particles (electrons, photons) have wave properties, their interference leads to the results exposed above. This interference cannot be presented exactly as a classical wave, but we accept that the probability to find a particle at some direction (angle $\theta_0 \pm d\theta$) is proportional to the square of the amplitudes (5) [3]. If many particles are identical (equal momentum $p = hk$, $k = |1/\lambda|$), then the results are the same as the previously obtained and we accept that the number of particles N must be proportional to the square of the corresponding amplitudes (5). For our special experiment (Fig. 1) we obtain

$$N_1 \sim |A_1(r, \theta_1)|^2, \qquad N_2 \sim |A_2(r, \theta_2)|^2. \tag{7}$$

In this way we can receive from (3) and (4):

$$N_1 \sim 4N_0 \cos^2\left(\frac{2\pi a}{\lambda}\sin\theta_1\right), \qquad N_2 \sim 16N_0 \cos^2\left(\frac{2\pi a}{\lambda}\sin\theta_2\right). \tag{8}$$

For the direction $\theta_1 = \theta_2 = \theta = 0$ one can obtain the ratio of the number of particles N_1 registered by the detector D only with the first barrier and the number of particles N_2 with the two barriers. Like the energy of the classical (sound) waves this ratio is

$$\frac{N_1}{N_2} = \frac{1}{4} \quad \text{or} \quad N_2 = 4N_1, \tag{9}$$

Evidently, this result (9) cannot correspond to the experiment with particles although it is true for the energy of a classical sound wave. Classical waves (Fig. 1) we accept as the waves in a continuous medium in the whole space of experimental arrangement. The modulus of amplitudes is constant and it is established in each point in the space and each moment of time. In some directions the modulus of amplitude has the maximums in some other directions, the modulus of amplitudes are smaller or zero. When an interference of particle is observed there is not a continuous medium and established amplitudes, but separate particle wave packages. N_1 is measured by a detector ($\theta_1 = 0$) and after the second barrier ($\theta_2 = 0$) the number N_2 cannot be greater than N_1 because N_1 must be distributed with different probability in all directions of θ_2. We must conclude that our definitions (7) cannot be used for the experiment with particles (Fig. 1).

To explain the contradiction (9) it is necessary to remember that each single particle can pass the experimental setup of Fig. 1 and the interference pattern should not change. To be more precise, in Fig. 2 is shown a scheme for interference of a single photon, which passes the two barriers successfully and reaches the detector D. In Fig. 2*a*) the wave package of the photon is located in front of the first barrier 1. When the wave package passes the two slits its wave ($\lambda = d/2$) creates the interference picture (different amplitudes in different directions θ_1) as shown in Fig. 2*b*). The particle (or our electromagnetic soliton) after interaction with the double slit must be found

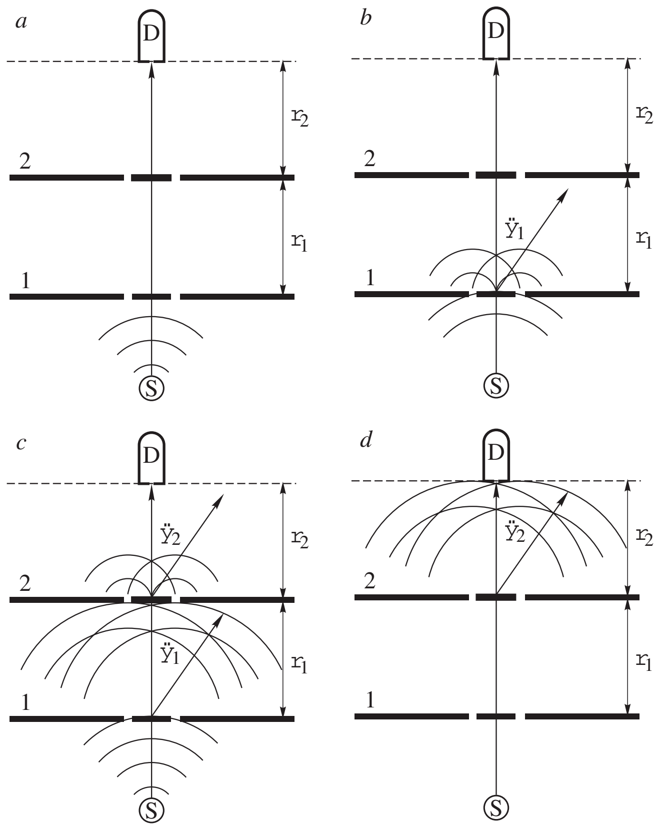

Fig. 2. The successive schematic representation of a photon-soliton wave package, which passes the two stage double slit: (*a*) wave package prior the first barrier 1; (*b*) the wave passing the first barrier form a wave package with different amplitudes in direction θ_1 and the particle soliton is placed in some of these directions with the corresponding probability; (*c*) the wave package reaches the second barrier and forms different amplitudes in directions θ_2. The probability to find the soliton in some direction θ_2 is proportional to $|A(\theta_2)|$; (*d*) the $\theta_2 = 0$ case, the soliton reaches the detector D.

with the known probability in some direction θ_1. Let this angle be $\theta_1 = 0$, when the wave package can pass the barrier 2. Here, the interference picture is repeated (Fig. 2*c*) and the particle (electromagnetic soliton) must appear with the known probability at some direction θ_2. If this probability corresponds to the direction $\theta_2 = 0$, the particle can be registered by the detector D (Fig. 2*d*). In all other directions of θ_1 and θ_2 the particle cannot be registered (it cannot reach the detector). One second particle emitted by the source S repeats the same as the first particle, but because of different probability the particle is located at other place and the detector could not register it.

If the wave packages of two or more particles coincide in time and space (and they are not coherent) the probabilities could not be the same and the location could not be predicted. This explains why the interference with an intensive beam of spontaneously emitted photons (with equal frequencies, but different phases) cannot be observed. When the photon packages are separate in space and time, each photon package interferes only with itself and the interference pattern is well defined.

These explanations, we think, are true for all particles (photon-soliton, electron, neutron, etc.). The wave packages of the particles have the same nature and now this is accepted to be the field of de Broglie with wavelength $\lambda = h/p$ (one prefers to speak about the wave function ψ). This explanation is also a consequence of the paper [4], which describes a numerical interference experiment with a classical particle on the surface of a liquid. The classical particle passes through one of the slits, but the surface wave-package passes through the two slits and interferes guiding the particle in some direction of the maximal amplitude. The directions where the modulus of amplitudes is zero are not allowed. When many classical particles (and the surface wave packages) pass (one after another) the two slits, the distributions of their numbers correspond to the experiments with electrons.

4 The Removed Contradiction

The contradiction (9) can be removed introducing the probability $W(\theta)$ to find one particle in some direction θ. This probability must be proportional to the ratio between possible direction of one particle and integral possibility for all directions. For the experiment (Fig. 2) (accepting $A_0 = 1$) these probabilities are

$$\begin{aligned} W_1(\theta_1) &\sim \frac{\cos^2\left(\dfrac{2\pi a}{\lambda}\sin\theta_1\right)d\theta}{\displaystyle\int_0^\pi |A_1(r,\theta_1)|^2 d\theta_1} \\ W_2(\theta_1) &\sim \frac{\cos^2\left(\dfrac{2\pi a}{\lambda}\sin\theta_2\right)d\theta}{\displaystyle\int_0^\pi |A_1(r,\theta_2)|^2 d\theta_2} \end{aligned} \tag{10}$$

The corresponding numbers of particles N_1 and N_2 are proportional to the probabilities (10). The two functions (argument θ_1 and θ_2), and their integrals (10) differ only in the corresponding constants of integrals. For directions $\theta_1 = \theta_2 = \theta = 0$ one can find the ratio

$$\frac{N_1}{N_2} = 4. \tag{11}$$

The number of particles N_1, which can be registered by the detector (for some fixed time) only with the first barrier and the number N_2 with the two barriers corresponds to our expectations. It is sure that when an experiment like described one is carried out with the particles (Fig. 2) the result must be $N_1 > N_2$, but the question is "how many times"? The question is based on our understanding of photon as a soliton and the constructions of different electromagnetic waves. All electromagnetic waves consist of the photon-solitons [1], but one must distinguish the classical and the laser electromagnetic waves from the waves of photons emitted spontaneously by the sources. As was mentioned in [1] an antenna (or laser) emits the photons synchronously and the wave package is very long in space and time. The spontaneous photons are emitted randomly in time and although the frequencies of the photons coincide (monochromatic), the wave packages of de Broglie are not coherent with one another. This implies a careful planning of the interference experiments with the photons.

5 Square of Amplitude or Amplitude

A long time ago it was known that in quantum physics interference phenomenon of the particles could be described in the terms of classical physics interference (continuous medium and established amplitudes), but this was only a mathematical tool which could not explain the nature of the particles' interference [3,5]. In the numerical experiments, with a classical particle on the surface of a liquid [4], the directions of propagation θ coincide with the directions of maximal amplitude of the surface wave. Above, we explained the interference of the photon-soliton wave package also with the amplitude (Fig. 2). It is known also that the number of particles cannot correspond to the energy (intensity) as it is for the classical wave. Now, with the two-stage interference experiment, there is an opportunity to check experimentally these two possibilities as well as some other problems. This check can be made in two ways. If not the square of amplitude, but only the modulus of amplitude is responsible for the possible particle directions, then for a definition of the probability $W_a(\theta)$ the modulus of the amplitudes (1) and (2) (for $A_0 = 1$) can be used.

$$
\begin{aligned}
W_{1a}(\theta_1) &\sim \frac{\left|\cos^2\left(\dfrac{2\pi a}{\lambda}\sin\theta_1\right)\right| d\theta}{\displaystyle\int_0^{\pi} |A_1(r,\theta_1)|^2 d\theta_1} \\
W_{2a}(\theta_1) &\sim \frac{\left|\cos^2\left(\dfrac{2\pi a}{\lambda}\sin\theta_2\right)\right|) d\theta}{\displaystyle\int_0^{\pi} |A_1(r,\theta_2)|^2 d\theta_2}
\end{aligned}
\tag{12}
$$

The ratio of these probabilities, proportional to the corresponding numbers of photons (for $\theta_1 = \theta_2 = 0$) is:

$$
\frac{W_{1a}}{W_{2a}} = \frac{N_1}{N_2} = 2. \tag{13}
$$

Evidently, such experiments can check the two possibilities – amplitude or square of amplitudes. The results (11) and (13) differ two times and this is easy to check.

This problem can be checked also when comparing the detailed results of an experiment in which the number of photons in respect to θ_1 is measured for a long time. The calculated results from (12) and (10) (normalized in maximums) are shown in Fig. 3. It is seen, that when the square of amplitude is used, the width of the experimental maximums will be smaller in comparison with the modulus of amplitude. In a careful and detailed experiment, this can be also observed.

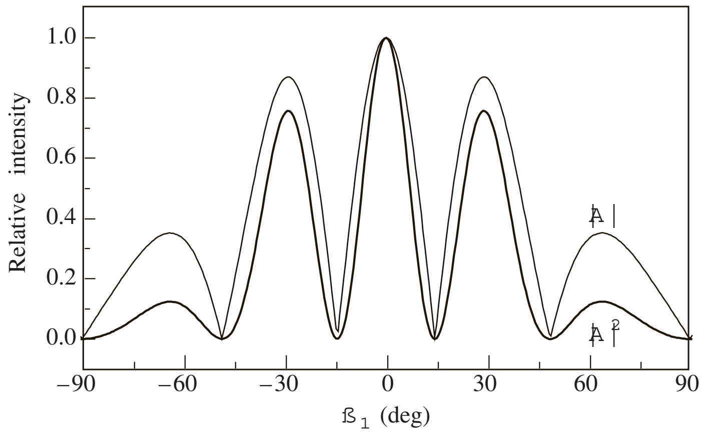

Fig. 3. A comparison between the functions $|W_{1a}(\theta_1)|$ Eq. (12) and $W_1(\theta_1)$ Eq. (10) normalized to the maxima. It is seen that the widths of the maxima $W_1(\theta_1)$ are narrow in comparison with the maxima of $|W_{1a}(\theta_1)|$. This difference could be observed experimentally.

6 Difference Between Classical Waves and the Photon-Solitons

In the double slit interference of the classical electromagnetic waves and the spontaneously emitted photons, probably exists some difference in the results. For a very long coherent wave package of the classical waves (e. g. laser beams) the intensities when using the two barriers can be proportional to the square of amplitude (3) and (4). When using the spontaneous emission of photons (not coherent, but separate in space and time wave packages) the ratio $\dfrac{N_1}{N_2}$ must correspond to (11) or (13).

The difference between the spontaneously emitted photons and these from the laser beam (although in equal numbers and frequencies) probably consists hi the fact that in a laser beam, the photons are coherent, but the spontaneous photons are not coherent. When the laser beam is very intensive [1], the electromagnetic particle-solitons must be arranged compactly in a very long coherent wave package, which electric field E changes as in the classical wave

$$E = \sqrt{K\omega^3}\,\sin(\omega t) \tag{14}$$

where $K = \dfrac{8m_0\hbar}{e^2}$ is explained in [1].

Schematically in Fig. 4 are shown the electric fields of the compactly arranged solitons (the fleshes) in a very long coherent wave package (14). Such a wave is consistent with a classical (e.g. sound) wave because in every point of space and in every moment of time (Fig. 1) there exists a continuous medium, electromagnetic field, with its electromagnetic amplitudes (different in different directions).

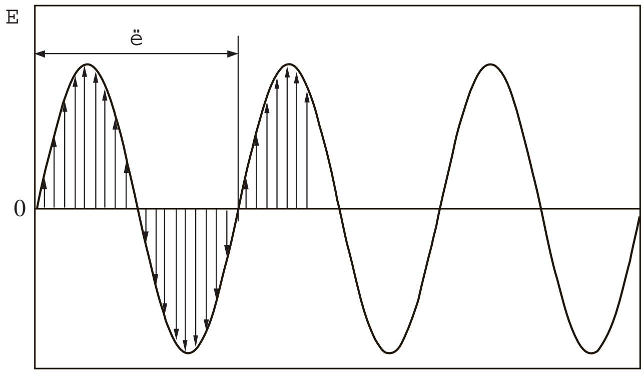

Fig. 4. The schematic representation of a wave obtained in a laser beam with many synchronized compactly arranged solitons (arrows) The long wave package is described as for every classical electromagnetic wave $E = \sqrt{K\omega^3}\,\sin(\omega t)$ [1,2].

If a laser beam (classical electromagnetic wave) is used for the double slit interference (Fig. 1), probably the intensities ($\approx N_1$ and N_2) can obey (3) and (4). Many particle-solitons pass simultaneously through the slits of the two barriers and there is not a difference from the classical assumptions.

As it is known, the intensity of a laser beam could be diminished many times (absorption of the photons or other methods) and the number of photons in the beam could be so rare in the time and the space like the spontaneous emitted photons. The difference between the spontaneously emitted photons and these from the laser beam (although in equal numbers and frequencies) probably consists in the fact that in a laser beam the photons are coherent, but the spontaneous photons are not coherent.

We cannot answer the question: what will be the result $\dfrac{N_1}{N_2}$ of the double slit interference (Figs. 1 and 2) between an intensive and a weak laser beam? Probably, for an intensive laser beam (classical electromagnetic field) the ratio $\dfrac{N_1}{N_2}$ will be (9), and for a laser beam with very low intensity (very rare in space and time solitons) this ratio will be (11) or (13). If this is so, then for the experiments with some middle intensity of a beam the results $\frac{N_1}{N_2}$ must pass from (9) to (11) or (13).

We hope that all these questions could be answered with the help of experiments described here: intensive and weak laser beams; spontaneously emitted photons and the photons arranged in a long coherent wave package. Therefore, the proposed here experiments could answer to many interesting (and exciting) questions.

These experiments are necessary for a more detailed examination of the structure of electromagnetic waves and the photons, but they cannot answer directly the question of the soliton reality. This question could be answered with the experiments, which use the other properties of our model of soliton, like these described in [1,2].

7 Other Experimental Possibilities with the Help of Double Slit Interference

In the paper [2] we propose some crucial experiments with the standing wave, which can help to distinguish the soliton structure of the photon in comparison with the classical assumptions of this wave. Here, we think, the same principals can be used for refute or confirm the existence of electromagnetic solitons. For this purpose, in Fig. 5 is shown schematically the modulus of the wave amplitude in direction $\theta_2 = 30°$ (Fig. 1). This direction is chosen because the wavelength of the photon wave is well-defined in comparison with the direction $\theta_2 = 0$, where for different wavelength exists maximum. The solitons in the wave package are marked with the fleshes. The critical amplitude E_c, corresponds to the threshold sensitivity of the detector. If electric field of a soliton E is smaller than E_c, the detector cannot register the soliton [2].

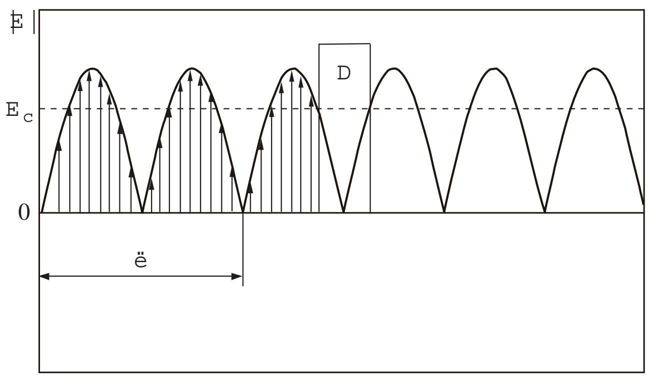

Fig. 5. The modulus of wave amplitude in direction $\theta_2 = 30°$. The solitons electric fields E are presented with the arrows. E_c is the field sensitivity of thin detector D. When the detector is in a place where $E < E_c$ the counting rate of the detector must be zero (like results of [2]).

In such experiments the sensitivity thickness of the detector must be very small (smaller than $\lambda/20$). In Fig. 5 the thin detector is marked as a vertical parallel plate. The place of this detector in the direction $\theta_2 = 30°$ could be changed with a small step ($\approx \lambda/20$). If the soliton electric field $E = \sqrt{K\omega^3}\,\sin(\omega t) \geq E_c$, then only the solitons in a small region about the maximums can produce a signal of the detector. Changing the place of the parallel detector in the direction $\theta_2 = 30^\circ$ the count rate in some places will be zero (for the zero of amplitude) and the maximum of the count rate will be at the maximum of the modulus amplitude. If this is a classical wave the probability for registration of the photons must be proportional to $|E|^2$ (like all results obtained in [2]). In this case the count rate of the detector would be maximal also at the place of maximal amplitude modulus, but never can be zero because the thickness of the detector could not be zero.

This qualitative experiment is more difficult in comparison with the experiments described in Sections 2 to 5. Such experiment requires a very great stability of the experimental arrangement because the thin detector must be placed at different positions with an exactitude comparable with $\lambda/20$. All thermal and mechanical problems must be solved as they are in the works [6,7]. By the way, the results of the experiments [6,7] evidently can be explained with the properties of our photon-soliton emitted synchronously by a laser (very rare in space and time, but coherent photon-solitons). The real wave package of de Broglie simultaneously passes in the two branches of interferometer with the help of the first mirror, but the particle-soliton passes always in one of the interferometer branches. When the coherent waves of the two branches interfere on the end of the interferometer (after the last mirror) the electromagnetic particle (soliton) appears only in the places where the amplitudes of de Broglie's wave are maximal. In the space where this amplitude is zero the soliton cannot be found.

These experiments confirm the model of electromagnetic waves described in this paper and the papers [1,2]. These experiments undoubtedly show the reality of de Broglie's wave and our model of the soliton.

8 Conclusions

The aims of this paper (and paper [2]) are to search new experimental possibilities for refuting or proving the reality of the constructed photon-soliton [1]. We now see that these aims are experimentally possible to be reached. The experimental facts confirming our soliton model are: interactions with hydrogen atom, classical cross-section of soliton [1], consistence between soliton energy density and the Planck density of energy of radiation [2], etc. Some of experiments cannot be understood without accepting the reality of de Broglie's wave, which governs the motions of the particles and this reality is on the base of the soliton. The reality of de Broglie's wave, we think is the main essential result obtained the soliton assumption.

We do not know any experimental fact, which contradicts the soliton, but we are convinced that it is necessary to search such facts because the existence of the solitons could change our understanding of the nature. We hope that this paper and the proposed experiments are a contribution to the problem.

References

[1] P. Kamenov and B. Slavov. Foundations of Physics Letters **11**(4) (1998) 325-342.

[2] P. Kamenov and B. Slavov. Foundations of Physics **14**(6) (2001).

[3] E. Wichmann. *Quantum Physics.* Berkeley Physics Course, vol. IV (Russian Ed., Nauka, Moscow 1974) p. 171.

[4] P. Kamenov and I. Christoskov. Phys. Lett. A **140** (1989) 13-18.

[5] R. Feynman, R. Leighton and M. Sands. *The Feynman Lectures on Physics.* Vol. 1 (Russian Ed. Mir, Moscow 1965) p. 203.

[6] C. Alley, O. Jakubowich, C. Steggerda, W. Wickes. In: Proc. Int. Symp. Foundations of Quantum Mechanics, Tokyo, 1983, pp 158-164.

[7] C. Alley, O. Jakubowich, W. Wickes. In: Proc. 2nd Int. Symp. Foundations of Quantum Mechanics, Tokyo, 1986, pp 36-52.