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REFINED MODEL FOR THE PASSAGE FROM CLASSICAL TO QUANTUM PHYSICS

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We review and refine a model which explains classical, as well as quantum results of the double-slit experiment. The model is deterministic, linear and rests on only two assumptions: particles may travel in different directions and are reflected by the borders of the slits. The change from classical to quantum behavior is very smooth and results from the variation of one or several parameters linked only with the possible directions of particles' movement.

Key words: double-slit experiment, classical and quantum behavior.

1. Introduction

In early studies [1-3] we introduced a model which can treat together quantum *and* classical problems. To be specific, we studied the famous double-slit experiment introduced by Feynman [4]. This "mind experiment" compares the movement of classical waves or particles and of quantum entities travelling through a Young-type interferometer. As is well-known, classical waves produce behind the screen an interference pattern with maxima and minima. Classical particles go through one or the other of the two slits without splitting and form just two maxima. As for the quantum micro-particles, they give an interference pattern acting like waves, but at the same time they travel as particles, without dividing in any way. Therefore the quantum interference pattern could be recorded even if particles pass through the device one at a time. A quantum particle is much smaller than all the geometrical distances of the experimental arrangement. There is no classical explanation to the path of such a small entity through one of the slits, the resulting pattern being developed as if the particle would go through both slits at a time. Speaking about the double-slit experiment Feynman noted that classical physics is unable to explain this phenomenon, which is the central point of quantum mechanics. Therefore Feynman indicated this situation as being the only quantum mystery.

Even though the double-slit experiment is very old, new research is conducted in this area and the outcomes are considered among first-rate results of

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experimental physics. Examples are “the most beautiful experiment in the world” of Tonomura et. al., [5], experiments with large molecules of Zeilinger and co-workers [6] and the recent electron-interference results of Bach et. al. published in March 2013 [7].

This is why we further investigate classical, as well as quantum results of a double-slit experiment, both contained in a simple classical model. It could be connected with quantum random walk [8], but the approach is rather different

The model is linear and depends chiefly on a single parameter, i.e. the probability for a particle to move in a straight line or to deviate from this direction along two symmetrical paths. By continuous variation of this probability both classical and quantum behaviors occur, the passage between them being as smooth as possible. Our conclusions are compared with known results from interference theory and the agreement is satisfactory, taking into account our unrefined model. Later we improve this agreement by introducing several new directions for the motion of particles. We end with a few comments and explanations of the model.

Our purpose is not to contest quantum results or interpretation, neither do we sustain that a classical explanation can prevail against quantum theory. Therefore this paper does not fit among theories trying to challenge quantum mechanics, as do for example hidden variable theories (see e.g. [9, 10]). In fact these attempts were contested by experimental work leading to the corroboration of quantum theory via Bell's inequalities [11, 12]. Other classical models based on stochastic mechanics lead to results similar to those of quantum mechanics [13]. However, our model, unlike these random models, is very simple and this is its main benefit.

2. Simple model with three directions

The arrangement is described in Fig. 1. Parameters indicated are: h – the screen thickness, d_s – the width of the source, d – the distance between the two slits, D_1 – the distance source-screen, $2w$ – the width of a slit and D – the distance screen-detectors.

The source emits *classical particles*. They travel mainly to the right with probability a, but some particles move away from the main stream, upwards or downwards, with equal probabilities indicated by b. Quantities a and b are connected by the relation $a + 2b = 1$ ([14]).

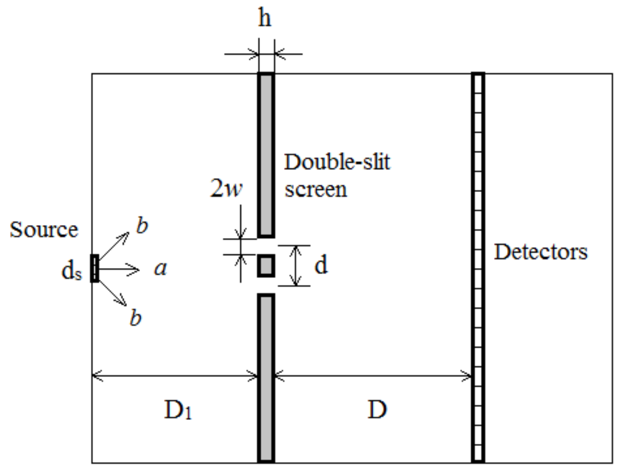

Fig. 1. Double-slit experimental arrangement.

To take into account these three possibilities we consider that the region through which particles go is a lattice formed by distinct cells, each of them divided into three compartments denoted by geographic names (*NE*, *E*, *SE*), as in Fig. 2. In order to observe clear patterns the entire area has dimensions comprised between 50×20 to 200×100 cells. Larger number of cells may be used, but the computation time increases accordingly.

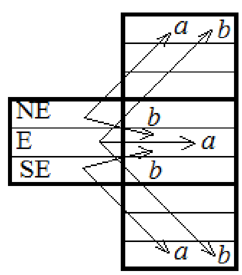

Fig. 2. Cell structure and probabilities for particle advance.

The same diffusion occurs for each cell. Denote the occupation probabilities for the sub-cells of cell (i, j) by $u_{NE}(i, j)$, $u_E(i, j)$ and $u_{SE}(i, j)$. The process of free movement is described by an obvious system of three linear difference equations, as in [1-3]:

$$\begin{aligned} u_{NE}(i,j) &= a\,u_{NE}(i-1,j-1) + b u_E(i-1,j-1) \\ u_E(i,j) &= b\,u_{NE}(i,j-1) + a\,u_E(i,j-1) + b\,u_{SE}(i,j-1) \\ u_{SE}(i,j) &= a\,u_{SE}(i+1,j-1) + b u_E(i+1,j-1) \end{aligned} \tag{1}$$

Particles spread from the source until they reach the two-slit obstacle. They are reflected by the borders of the slits [15]. Reflected and diffused particles mix together and eventually arrive to a line of detectors. Here the contents of the three subcells are added and their total number, called cumulated amplitude, is presented as a function of the detector position. As a general rule, if parameter *a* is smaller than 0.9, one gets a "classical behavior" without interference, as in Fig. 3a. When the two slits are close enough (*d* less than 10 cells), one obtains only one central maximum.

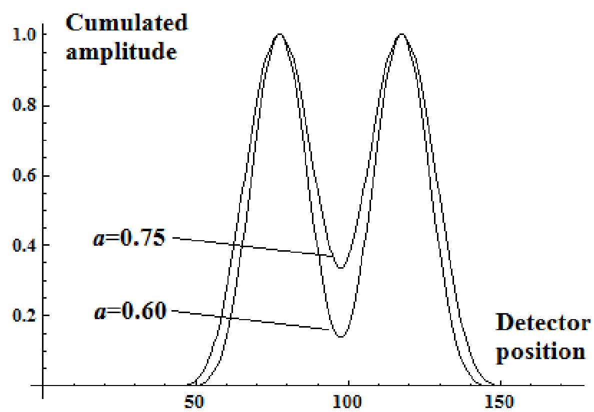

Fig 3a). Cumulated amplitude for the classical case for two values of the probability parameter *a*=0.60 and *a*=0.75.

In order to find a "quantum behavior" the only detail we have to change is the value of *a*, the probability of forward movement of the particles. By increasing this parameter, on top of the smooth curves from Fig. 3a superposes a series of spikes. For *a*>0.9 these spikes grow until a clear interference pattern appears as in Fig. 3b. In reality the pattern acquired by simple use of the equations (1) has several fake maxima. We eliminate them by averaging the cumulated intensity over five "detecting cells".

Fig. 3b presents a comparison of our results with a curve computed by Van Cittert-Zernike theorem for the interference of quasi-monochromatic light. (see e.g. [16]). The centered detector position is calculated with respect to the central maximum of the pattern. Only the central maxima and minima can be fitted in this simple model with just three directions.

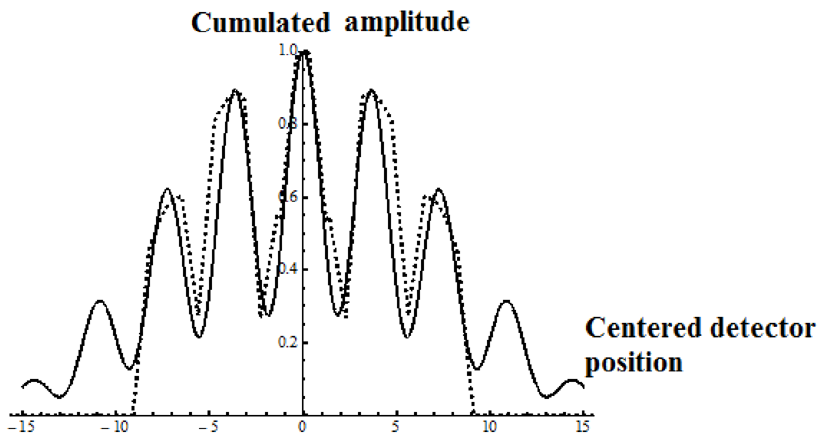

Fig.3b). Comparison of the model for three directions of possible movement. Dashed curve: cumulated amplitude for the quantum case, *a*=0.97; continuous curve: predictions from quasi-monochromatic interference theory. The pattern is smoothed by averaging over five detectors.

3. Model with five or seven directions

We refine the model by permitting the particles to move in five directions. Results for $a<0.9$ are analogous to those from Fig. 3a. For $a>0.9$ the results of our model are compared with the same calculation from the theory of interference of partial coherent waves. They are presented in Fig. 4.

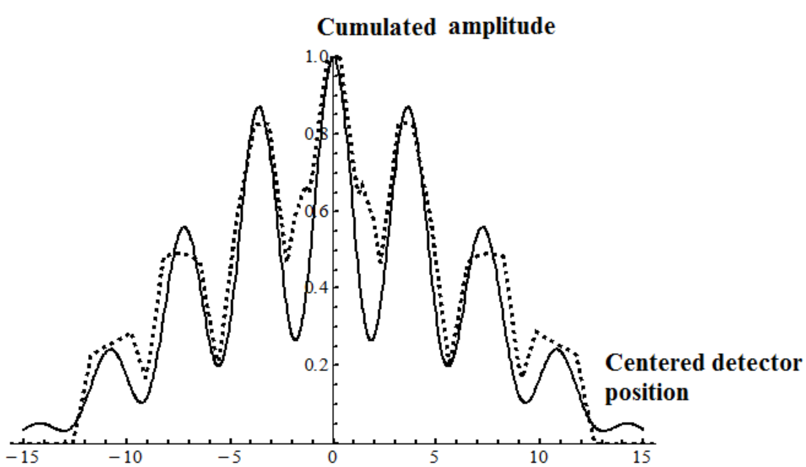

Fig. 4. Comparison of the model for five directions of possible movement. Dashed curve: cumulated amplitude for the quantum case, *a*=0.97; continuous curve: predictions from quasi-monochromatic interference theory. The pattern is smoothed by averaging over five detectors.

The above figure shows a much better matching between our model and classical results. We expect the same improvement when going to seven directions. This is not so obvious from Fig. 5, but the number of well-matched fringes grows when the number of directions increases.

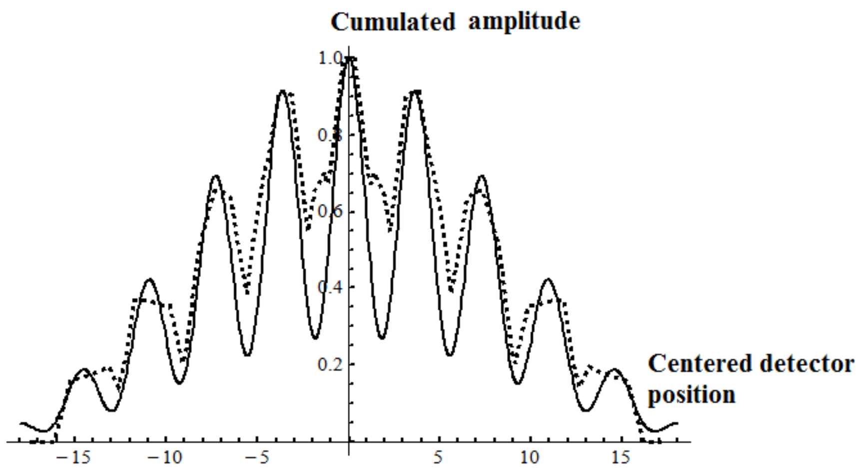

Fig.5. Comparison of the model for seven directions of possible movement. Dashed curve: cumulated amplitude for the quantum case, a=0.97; continuous curve: predictions from quasi-monochromatic interference theory. The pattern is smoothed by averaging over five detectors.

4. Discussion and conclusions

Our linear model is rather unsophisticated. Particles move through a lattice diffusing in three, five or seven directions. For the simplest case of three directions, the only variable is parameter a, which measures the probability to move forward. Parameter b is fixed by the condition $a + 2b = 1$. Modification of a is sufficient to pass from the classical behavior from Fig. 3a to the quantum comportment as in Fig. 3b. Model with five directions contains three parameters, denoted by a, b and c, linked by the condition $a + 2b + 2c = 1$. It is easy to choose values for two of them and go smoothly from classical to quantum behavior. The same is true for seven directions, where the four parameters are connected by the condition $a + 2b + 2c + 2e = 1$. Allowing more directions the agreement between our results and those from classical interference theory becomes better and the fitted number of maxima and minima grows as may be observed from Figs. 3b, 4 and 5. Therefore we are confident that the model is consistent.

We have no explanation for the threshold value of parameter a which breaks up classical and quantum behavior.

Parameters indicated in Fig. 1 may well be modified to obtain convenient pictures, but the general structure of the patterns does not change significantly. All these quantities are to be measured in terms of "cells". For instance, if the screen has a thickness of just two cells, maxima are very weak, but the shape of the pattern is the same as those in Figs. 3-5. The same changes appear if the source has but one cell. In the particular situation when the two-slit screen is replaced by an opaque obstacle, the Fresnel spot is apparent behind the obstacle [3].

It has to be remarked that interference does not appear from superposition of waves, but from two processes typical for particles:

- spreading about the forward direction of movement
- reflection on the borders of the slits.

We have analyzed several conditions of this reflection and always found analogous forms of the final pattern.

Studies will continue on the following topics:

- Variation of parameters along the path
- Increasing the number of possible directions
- Changing the limit conditions on the frontiers of the slits
- Minimal conditions under which the pattern changes from classical to quantum form.

R E F R E N C E S

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[14]. For the East-going particles this is a conservation condition. But as may be seen from Fig.2 we do not impose the same requirement for particles in *NE* or *SE* sub-cells. This occurrence results in a lack of overall normalization and we lose particles moving in the *N* and *S*

directions. Actually this circumstance does not perturb the final pattern. Particles moving about *N* and *S* as well as those going back to the left do not pass through the slits and are not counted by any of the detectors.

[15]. See details in ref. [2]. We tested various methods to compute the influence of the borders: reflection in the same cell, reflection in the next cell, reflection without diffusion, different reflection coefficients. In all computed situations the global pattern has similar characteristics.

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