Quantum interference with macroscopic objects

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Abstract. We demonstrate that an interference pattern is not only characteristic for a wave (packet) but that it can also be build up by many particles arriving one by one at a detector without direct information exchange between the particles. We also demonstrate that full which-path information does not necessarily rule out interference effects. We illustrate this by an interference circuit for people. Our results prove that it is possible to give a particle-only description of single-particle interference experiments without first solving a wave equation.

Keywords: Interference, particle-wave duality, computer simulation
PACS: 02.70.-c , 42.50.Dv, 03.65.-w

INTRODUCTION

Particle-wave duality, a concept of quantum theory, attributes to photons (light quanta) the properties of both wave and particle behavior depending upon the circumstances of the experiment [1]. The particle behavior of photons has been shown in an experiment composed of a single 50/50 beam splitter, of which only one input port is used, and a source emitting single photons and pairs of photons [2]. In what follows we refer to this experiment as experiment I. Using an idealized pictorial description of this experiment one could say that every time one photon of a pair is detected at a detector placed on one side of the source, only one of the two detectors placed behind the beam splitter on the other side of the source gives a click. Hence, since in this idealized picture the two detectors behind the beam splitter never give a click simultaneously, wave behavior is excluded and the photon is said to behave as a particle [2]. The wave character of the photon has been demonstrated in a single-photon Mach-Zehnder interferometer experiment [2], an extension of experiment I and referred to as experiment II. In this experiment the normalized detector counts $N_1/(N_1+N_2)$ and $N_2/(N_1+N_2)$, N_1 and N_2 denoting the number of detection events registered at detectors P_1 and P_2 placed behind the second beam splitter of the interferometer, are given by $\cos^2\Phi$ and $\sin^2\Phi$ where Φ denotes the phase difference between the two interferometer arms, which is the same result as if the source would have emitted a "classical light wave". In experiment II an interference pattern is observed, which is commonly considered to be characteristic of a wave. Also in a single-photon two-slit experiment [3], referred to as experiment III in what follows, an interference pattern is observed. It is said that in the previous experiments the photon behaves either as a particle (experiment I) or a wave (experiment II and III).

Now, one could ask the question why the three experiments described above are so-called quantum experiments. The three experiments have in common that, if one analyzes the data after N detection events, long after the experiment has finished, the averages of the detection events agree with the results obtained from wave theory, that is with the classical theory of electrodynamics (Maxwell theory). In experiment I [2] one obtains a constant intensity of 0.5 at both detectors, in experiment II [2] one obtains an interference pattern as a function of Φ and in experiment III one observes an interference pattern at the detection screen. However, the single anticorrelated detection events observed in experiment I clearly indicate that the source is not emitting waves but so-called single photons [2]. Also, experiments II and III are carried out in the single-photon regime [2, 3]. Hence, the input to the three experiments seem to be single photons (light quanta), but then the question arises how to interpret the output which seems to show particle or wave character depending on the circumstances of the experiment. This question is not limited to photons. Already in 1924, de Broglie introduced the idea that also matter can exhibit wave-like properties [4]. This idea has been confirmed in various double-slit experiments with massive objects such as electrons [5–8], neutrons [9, 10], atoms [11, 12] and molecules such as C_{60} and C_{70} [13, 14], all showing interference.

In experiment I, although the average results after many detection events can be described by classical wave theory, one can obtain full which-path information (WPI) of the incoming photons, a property associated to particle behavior. Hence, one could give a complete description of experiment I in terms of particles. In experiments II and III, the average results after many detection events can also be described by classical wave theory, but now one observes interference fringes, associated to wavelike behavior, and no full WPI of the incoming photons can be obtained in the experiments. To resolve this apparent contradiction in the behavior of the photons, quantum theory introduces the concept of particle-wave duality [1]. Therefore this type of experiments are called quantum experiments and explanations of the experiments are frequently given in terms of single photons and particle-wave duality.

However, the pictorial description using concepts from quantum theory, when applied to individual detection events (not to the averages) leads to conclusions that defy common sense: The photon seems to change its representation from a particle to a wave while traveling from the source to the detector in experiments II and III. This should not be a surprise: It is commonly accepted that quantum theory gives us a recipe to compute the frequency (averages) for observing events, but does not describe individual events [1]. Although not applying this reasoning to describe this type of experiments could prevent us from making nonsensical conclusions, this unfortunately would not give us a single clue as how to explain the fact that individual events are observed experimentally and, when collected over a sufficiently long time, yield averages that agree with wave theory. Since no theory seems to exist that can give a sensical description of the "whole" experiment, we adopted the idea to search for algorithms that could mimic (simulate) the detection events and experimental processes. In [15] and [16] we described models that, when implemented as computer programs, perform an event-by-event simulation of experiments I and II [2] and III [3], respectively. The simulation model is solely based on experimental facts, satisfies EinsteinŠs criterion of local causality and does not rely on any concept of quantum theory or of probability theory. Nevertheless, our simulation model reproduces the averages obtained from the wave theoretical description of experiments I, II and III but as our approach does not rely on concepts of quantum theory

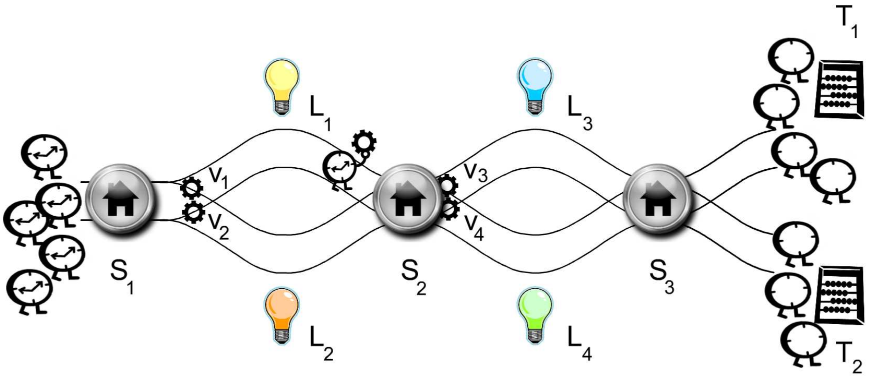

FIGURE 1. (Color online) Schematic diagram of an interference experiment with humans. S_1, S_2, S_3 denote data processing stations, v_i, (L_i) with $i = 1, \dots 4$, denotes the speed of the conveyor belt (color of the light observed) in the four respective tracks and T_1 and T_2 denote counters counting the people leaving one of the two possible exits of the circuit.

and gives a description on the level of individual events, it provides a description of the experimental facts that does not defy common sense. In a pictorial description of our simulation model, we may speak about "photons" generating the detection events. However, these so-called photons are elements of a model or theory for the real laboratory experiment only. The experimental facts are the settings of the various apparatuses and the detection events. What happens in between activating the source and the registration of the detection events is not measured and is therefore not known. Although we always have full WPI of the individual photons (we can always track the photons during the simulation), the photons build up an interference pattern at the detector. Although, the appearance of an interference pattern is commonly considered to be characteristic for a wave, we have demonstrated that, as in experiment, it can also be build up by many photons. These photons have full WPI, never directly communicate with each other and arrive one by one at a detector.

In this paper, we demonstrate that an interference pattern can be build up by many non-interacting particles arriving one by one at a detector and this irrespective of their size. As an example we give a set of rules to produce an interference pattern with people travelling through a circuit that is the equivalent of a chained Mach-Zehnder interferometer (see Fig. 1). These people have full WPI, are not allowed to directly communicate with each other, arrive one by one at a detection station and nevertheless produce an interference pattern.

(QUANTUM) INTERFERENCE WITH HUMANS

Figure 1 shows the schematic diagram of the interference experiment with humans. We assume that the circuit consists of four conveyor belts running with adjustable speed connected to short conveyor belts in the stations running at fixed speed. Except from the labeling of the conveyor belts with four lights L_1 (yellow), L_2 (orange), L_3 (blue) and L_4 (green), this diagram maps onto the network of two chained Mach-Zehnder

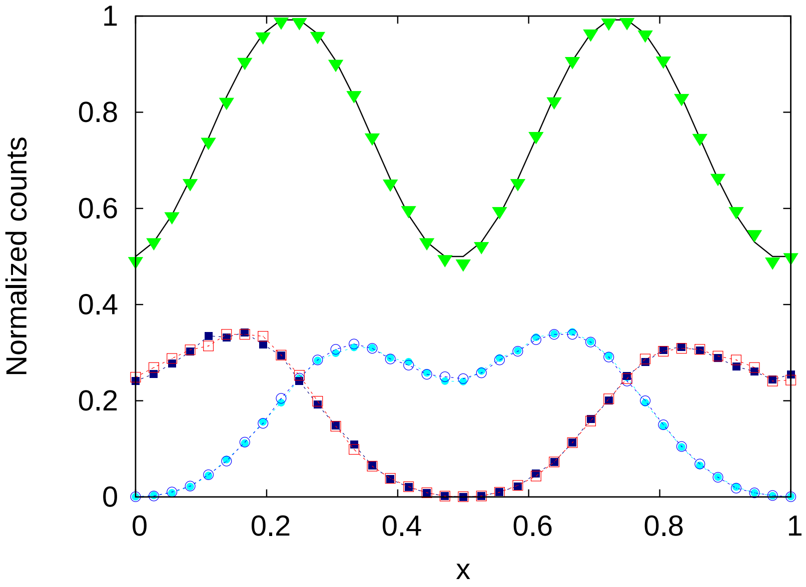

FIGURE 2. (Color online) Simulation results for the interference experiment depicted in Fig. 1. The length of the four conveyor belts is fixed to 60 m. Their velocities are $v_2 = v_3 = 1$ m/s, $v_1 = v_2/(1+x)$ and $v_4 = v_2/(1+x+\delta)$, where x and δ control the relative speeds. We take $\delta = 1/36$ and vary x. Markers give the results for the normalized intensities $N_1^{L_1,L_3}/N$ (open circles), $N_1^{L_2,L_3}/N$ (solid circles), $N_1^{L_1,L_4}/N$ (solid squares), $N_1^{L_2,L_4}/N$ (open squares) and N_1/N (triangles) as a function of x, where N_1 denotes the total number of people counted in station T_1. For each value of x, the number of people participating in the experiment $N = 10000$. Results are obtained for $\alpha = 0.99$. The solid line represents the result of quantum theory given by $N_1/N = (1+\sin 2\pi x \sin 2\pi(x+\delta))/2$. The other lines are guides to the eye.

interferometers [17]. The people, the stations S_i $(i = 1,\ldots 3)$, the velocities v_i $(i = 1,\ldots 4)$ and the counters T_i $(i = 1,2)$ play the role of the photons, the beam splitters, the phase shifters and the detectors, respectively. Persons are waiting in front of station S_1 to enter the circuit. Only one person at a time is allowed to travel the circuit, that is only as soon as one of the counters T_1 or T_2 register the arrival of a person, the next person is allowed to enter S_1 and proceed. All persons carry a clock measuring their travel time t. The clocks have only one hand that makes a full circle in one minute. The position of the clock's hand is most conveniently represented by a two-dimensional unit vector $\mathbf{e} = (e_0, e_1) = (\cos\phi, \sin\phi)$, where $\phi = 2\pi t$ min^{-1}. The hand of the clock is put in upward position, that is $\mathbf{e} = (0,1)$, before entering S_1. All persons are asked to remember the two light colors they will observe while traveling the circuit. This information has no counterpart in the single-photon Mach-Zehnder interferometer experiments [2, 15, 17]. It clearly provides WPI but it can be omitted in the final data analysis, as we show later.

The persons can be seen as playing the role of messengers carrying their travel time and eventually the observed light colors as a message. When the nth person arrives at a station, the station operator reads the person's clock and asks which light color (L_1 or L_2) the person has observed. Observation of a yellow (orange) or green (blue) light corresponds to arrival at entrance port $k = 1$ $(k = 0)$ of S_2 or S_3, respectively. In S_1 only one entrance port is used. Note that the light color is not strictly necessary to label the entrance ports. The entrance and exit ports are also automatically labeled by the arrival and departure via the upper or lower conveyor belts, that is in S_2 (S_3) the incoming upper conveyor belt defines the $k = 1$ ($k = 0$) entrance port and the outgoing upper (lower) belt defines the $k = 0$ ($k = 1$) exit port. Each station operator has two blackboards which contain two numbers between minus one and one and one blackboard with two numbers x_0, x_1 between zero and one. If the person enters at port 0 (1) he first replaces the two numbers $y_{0,0}$, $y_{1,0}$ ($y_{0,1}$, $y_{1,1}$) on the first (second) blackboard by the two components of the clock's position e_0 and e_1. Having updated the numbers on his first or second blackboard, the station operator replaces the two numbers x_0, x_1 on his third blackboard using the rule $x_{i,n} = \alpha x_{i,n-1} + (1-\alpha)\delta_{i,k_n}$, where $i = 0, 1$ and $0 < \alpha < 1$. He then employs the six numbers on his three blackboards to calculate four numbers $w_1 = (y_{0,0}\sqrt{x_0} - y_{1,1}\sqrt{x_1})/\sqrt{2}$, $w_2 = (y_{0,1}\sqrt{x_1} - y_{1,0}\sqrt{x_0})/\sqrt{2}$, $w_3 = (y_{0,1}\sqrt{x_1} - y_{1,0}\sqrt{x_0})/\sqrt{2}$ and $w_4 = (y_{0,0}\sqrt{x_0} + y_{1,1}\sqrt{x_1})/\sqrt{2}$, and chooses a uniform random number r between zero and one. If $w_1^2 + w_2^2 < r$ the station operator tells the person to take exit port number 0 and changes the position of the hand of his clock to $(e_0, e_1) = (w_1, w_2)$. Otherwise, the person is told to leave via exit port number 1 while the position of the hand of his clock is changed to $(e_0, e_1) = (w_3, w_4)$. The station operators of S_1, S_2 and S_3 strictly follow the same procedure. Hence, in principle S_1, S_2, S_3 (and their operators) are interchangeable just as the beam splitters are in a single photon experiment.

The operators of stations T_1 and T_2 simply count the number of people arriving in their station. Since they can ask the persons which pair of colors they observed during their journey, both operators have four counters denoted by $N_i^{L_1,L_3}$, $N_i^{L_2,L_3}$, $N_i^{L_1,L_4}$ and $N_i^{L_2,L_4}$, where $i = 1, 2$ refers to station T_1, T_2, respectively. Calculation of $N_i/N = (N_i^{L_1,L_3} + N_i^{L_2,L_3} + N_i^{L_1,L_4} + N_i^{L_2,L_4})/N$ ($i = 1, 2$) for a fixed setting of the velocities v_i ($i = 1, \ldots 4$) and for a sufficiently large number of participants N, gives numbers that agree with those of quantum theory [17]. Repeating the experiment with different settings of the velocities results in an interference pattern [17]. An example is shown in Fig. 2. Note that if the operators of stations T_1 and T_2 ask the persons for the observed colors then an interference pattern is built up while full WPI is available. Hence, full WPI does not exclude interference. However, in many interference experiments it is impossible to obtain both an interference pattern and WPI, because not enough independent information is available. If the information needed to obtain knowledge of the followed path is also used to construct the interference pattern then only WPI or interference will be observed.

CONCLUSION

We have demonstrated that an interference pattern can be build up by many non-communicating particles having full which-path information and arriving one by one at a detector and this irrespective of the size of the particles. Hence, full which path information does not exclude interference or vice versa.

ACKNOWLEDGMENT

We would like to thank F. Jin for many helpful comments. This work is partially supported by NCF, the Netherlands.

REFERENCES

1. D. Home, *Conceptual Foundations of Quantum Physics* (Plenum Press, New York, 1997)
2. P. Grangier, G. Roger, A. Aspect, Europhys. Lett. **1**, 173 (1986)
3. V. Jacques, E. Wu, T. Toury, F. Treussart, A. Aspect, P. Grangier, J.F. Roch, Eur. Phys. J. D **35**, 561 (2005)
4. L. de Broglie, Annales de Physique **3**, 22 (1925)
5. C. Jönsson, Zeitschrift für Physik **161**, 454 (1961)
6. P.G. Merli, G.F. Missiroli, G. Pozzi, Am. J. Phys. **44**, 306 (1976)
7. A. Tonomura, J. Endo, T. Matsuda, T. Kawasaki, H. Ezawa, Am. J. Phys. **57**, 117 (1989)
8. M.W. Noel, C.R. Stroud Jr, Phys. Rev. Lett. **75**, 1252 (1995)
9. A. Zeilinger, R. Gähler, C.G. Shull, W. Treimer, W. Mampe, Rev. Mod. Phys. **60**, 1067 (1988)
10. H. Rauch, S.A. Werner, *Neutron Interferometry: Lessons in Experimental Quantum Mechanics* (Oxford Univ. Press, London, 2000)
11. O. Carnal, J. Mlynek, Phys. Rev. Lett. **66**, 2689 (1991)
12. D.W. Keith, C.R. Ekstrom, Q.A. Turchette, D.E. Pritchard, Phys. Rev. Lett. **66**, 2693 (1991)
13. M. Arndt, O. Nairz, J. Vos-Andreae, C. Keller, G. van der Zouw, A. Zeilinger, Nature **401**, 680 (1999)
14. B. Brezger, L. Hackermüller, S. Uttenthaler, J. Petschinka, M. Arndt, A. Zeilinger, Phys. Rev. Lett. **88**, 100404 (2002)
15. H. De Raedt, K. De Raedt, K. Michielsen, Europhys. Lett. **69**, 861 (2005)
16. F. Jin, S. Yuan, H. De Raedt, K. Michielsen, S. Miyashita, submitted to Found. Phys. (2009)
17. K. De Raedt, H. De Raedt, K. Michielsen, Comp. Phys. Comm. **171**, 19 (2005)