The unmysterious behavior of the photons in the double-slit experiment

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Abstract: Simultaneous observation of the wave-like and particle-like aspects of the photon in the double-slit experiment is unallowed. The underlying reason behind this limitation is not understood. In this work we propose an explanation for the impossibility of detecting the complimentary aspect of the photons by considering the information capacity of the photons. We show the single photons in the double-slit experiment have a very limited communication capacity that forbids them from carrying more than one message. In such systems only measurements associated with one proposition can obtain a physical result and the later measurements associated with independent propositions must necessarily contain an element of randomness. The elucidation we offer is based on the mathematics of information theory and does not make use of Heisenberg's uncertainty relation in any form.

1. Introduction

The single-photon Young's double-slit experiment is described as the experiment that "has in it the heart of quantum mechanics" (1). In the basic version of this experiment, a light beam illuminates a plate pierced by two parallel slits, and the light passing through the slits is observed on a screen behind the plate forming an interference pattern. The experiments performed by sending single photons show that they also collectively form an interference pattern (2-5) which is incompatible with the pattern of single particles that go through either of the slits. One may wonder what path the single photons take when they form an interference pattern. However, any attempt to determine the path of the photons destroys the interference pattern.

Many studies have confirmed this feature that an experiment designed to observe the wave-like interference necessarily gives up the option of observing the particle-like trajectories and vice versa (6, 7). Any effort to force the observation of both effects introduces an element of randomness that makes the results non-conclusive (8). Thus presenting a fundamental limitation on what aspects of the behavior of a quantum particle can be measured: obtaining the which-way information of the photons inhibits observing their wave-like property and observing their wave-like property inhibits obtaining the which-way information of the photons.

The underlying truth behind such strange behavior is not understood and the wave-particle duality is considered as the main point of demarcation between quantum and classical physics. Here, we propose an explanation for this limitation on obtaining complementary information about the behavior of the single photons in the double-slit experiment by taking into account that physical systems not only carry energy, momentum, etc. but also carry information.

2. **Information capacity of physical systems**

Physical systems can store data on their adjustable properties and convey messages. Any person who has played an "escape room" game knows that the needed information could be loaded even on the shape of a paper, or it's color. An adjustable property of a physical system with d distinguishable states can be loaded to carry a message worth up to $\log_2 d$ bits of data. The information capacity of a physical system can be calculated by summing up all independently adjustable properties of the system. A physical system with N number of adjustable properties, each with d_n distinguishable states, can carry N independent messages each containing up to $\log_2 d_n$ bits of data.

The messages and pieces of information loaded on those physical properties can be read later using appropriate physical measurements. One should note that once a measurement on a property of a system is done and the stored message on that property is read (say the color), an additional measurement on the same property (say the wavelength of the incoming light) does not give away any independent piece of information; the new result provides a measure of the mutual dependence between the two correlated measurements.

Generally, the capacity of macroscopic physical systems for storing information is huge, while bounded (9). A macroscopic object, like a token, can have many adjustable properties, such as temperature, color, and radius. Many such attributes, however, cease to exist in a well-defined manner in the microscopic realm. Therefore, the microscopic physical systems usually have a much less number of independently adjustable properties and accordingly, a much lower information capacity compared to macroscopic physical systems. For example, attributes such as color or temperature are not well-defined for an elementary particle like an electron, and it has only a few independently adjustable properties: energy, position, and spin. As in other physical systems, the degrees of freedom of the electrons may also be used for the storage and transmission of information.

3. Photons in the double-slit setup

A photon is a physical system with only a few numbers of degrees of freedom which makes its capacity to transmit messages very limited. Photons have only three independently adjustable properties that may be used as information carriers to convey messages: position, frequency, and spin. These properties of photons are those utilized in many 3D movie theatres using *'polarized 3D systems'* to respectively convey the shape, color, and depth perception of the moving pictures. In any case, a single photon can at most convey three independent messages[1].

Earlier we mentioned the strange behavior of single photons in the double-slit experiment. Setting up a double-slit experiment however, requires certain arrangements. For example, an ordinary light source, like a candle, would not produce an interference pattern. To observe the interference, all of the incoming photons must be highly directional, originate from the same location, and also be coherent so their energies are the same. Using a laser source provides these conditions and has made demonstrating such experiments more readily possible in physics' department labs (10).

In other words, when performing the double-slit experiment one needs to use a stream of photons that all come from the same source and have equal energy. These prerequisites fix the position and energy of the incoming photons and leave the interacting photons with only one non-fixed degree of freedom. Thus the photons in the double-slit experiment are physical systems with a single degree of freedom and can convey at most one message.

This explains the nature of the unique behavior of the photons in the double-slit experiment and the reason why the photons cannot carry two independent pieces of information. The photons in the double-slit experiment setup are physical systems that are left with only one degree of freedom, and thus they can convey at most one message. Once a measurement is performed on them, a second measurement associated with any other independent proposition must necessarily contain an element of randomness. Randomness indicates the measurement is performed on a system that has reached the state of zero information content (see Appendix II). This explains the observed

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[1] One may encode much more than three different pieces of information on a photon: see appendix I for a discussion about physical information (carried by the system) *vs.* semantic information (inferred from the message), in which the latter benefits from a wealth of shared background knowledge.

randomness in the experiment when the observation of the complementary effects is forced. Furthermore, this means such randomness is ontological and not removable.

4. Conclusion

In classical physics, the dynamics of a particle's evolution is governed by its position and velocity. In quantum mechanics, the uncertainty principle forbids simultaneous determination of the trajectory and momentum of a quantum particle, as in the photons in the double-slit experiment. No further explanation is offered for this fundamental limitation.

Our approach for explaining the photon's behavior in the double-slit experiment does not make use of Heisenberg's uncertainty relation in any form. We based the discussion on the fact that physical systems can store data and convey messages. With this aspect of physical systems being not unbounded, we found that in certain cases, such as the case of the photons in the double-slit experiment setup, the physical system can reach the lowest limit of their capacity to hold just one message. The same argument can be made for each of the macroscopic molecules in the carefully prepared homogeneous beam of the macromolecule selected for performing the interference experiments with large molecules (11, 12).

The unfamiliar case of single photons in the double-slit experiment is thus due to the situation that involves performing measurements on a system that can convey no more than one message: one can perform an experiment to find out about either which slit the photon has gone through or about its wave properties. This is far different from our classical experiences with systems that can simultaneously store and convey many different messages. Nevertheless, it shouldn't be surprising that an elementary particle like a photon would not have a large capacity to simultaneously hold different pieces of information.

It has not been unknown that physical systems can be used as communication devices or data storages (9), however, it appeared that information considerations do not affect the behavior of the physical systems. We discussed that in the extreme case of reaching very low information capacity, such as the photons in the double-slit experiment, mathematics forbids obtaining two informationally distinct outcomes. Furthermore, reaching the bottommost limit of information capacity, i.e. zero information, must necessarily contain an element of randomness, which is suggestive for quantum randomness.

The picture we presented in this paper, single photons as the physical systems with very limited communication capacity, can explain where the strange behavior of the photons in the double-slit experiment comes from; the experiment that Feynman called an experiment “has in it the heart of quantum mechanics” (1). This picture can potentially have more implications in interpreting quantum physics and can be a first step in grasping the physical meaning of the theory.

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Appendix I: Information vs. inference

One may wonder about a claim such that an electron can convey at most three distinct messages on its position, momentum, and spin. Is it not that possible to load, for example, three messages just on the different components of its momentum?

Here we should differentiate between our notion of information (semantic information) in contrast to physical information (information carried by physical objects). In short, our semantic information is what gets inferred and interpreted in a web of shared background knowledge and implied assumptions, but physical information bears no such references and comes in one chunk.

For example, one may use a beam of laser with adjustable wavelength –say sharply with values between 100 to 999 nm– to send a message to the other party. The information to be sent will be encoded on the wavelength of the light. With this setup, the physical carrier conveys a message worth up to $\log_2 899 = 9.8$ bits of data. In the receiving end, however, the wavelength measured in nm can be converted to binary (a number between 0001100100 and 1111100111) in which the value on each placing can represent the answer to a different pre-assigned yes/no question, 9 in total. With such encodings and wise choice of the questions, one can transmit a wealth of information just by using the wavelength of a laser. So it seems that the energy of photons can convey a lot more than just one message.

One should, however, not confuse this human ability to encode many pieces of information on the wavelength of a beam of light, that benefits from many shared background knowledge, with the physical messages that bear the information. In such encodings we implicitly or explicitly benefit from myriads of shared background knowledge between the agents at the ends, e.g. they both know what is a wavelength, nm, number bases, the choice of the questions, their order, the language in which the questions are in, etc. which are none part of the transmitted physical message.

Similarly, a single electron does not carry on itself per se the background knowledge of e.g. spatial directions, so that the observer at the receiving end be able to project and read the momentum in specific directions. In practice, the physical information is what is transmitted physically between the two ends and therefore the physical messages are distinguishable only based on possible distinct physical properties of the message carrier. Meaning, that a physical property with a huge number of states for example, physically bears messages in only one chunk; a big chunk though as it contains a large amount of data equal to $\log_2(\#\text{states})$ bits.

Appendix II: What does zero information means in physics

Physical information is extracted from physical objects with the act of measurement. When we perform a measurement we always get a reading; even a ‘zero’ reading is still a result and obtained information. Thus in physical world zero information cannot be assumed to be equivalent to zero data. Physical zero information means that the collected data represent zero information.

The information content of a message, which is composed of bits of data, can be evaluated mathematically. In the mathematical language of the information theory, as we show, physical zero information means that the result we collect should be either the same old reading or, a random reading since randomness is an expression of zero information.

Mathematically the expected information gain in a process involving possible outcomes of $X = \{x_1, x_2, x_3, \ldots\ldots\}$, is defined as the change in the Shannon entropy (13)

$$I = H_2(X) - H_1(X), \tag{1}$$

in which the Shannon entropy is defined as

$$H_t(X) = -\sum P_t(x_i) \log_2 P_t(x_i), \tag{2}$$

where $P_t(x_i)$ are the probabilities of the outcomes.

We can easily verify the two cases in which the information gain is zero. In the case of no new data, when one keeps getting the same result r, we have $P_t(r) = 1$ and hence $H_t(X) = 0$ and $I = 0$. In the case of randomness, the outcomes do not follow a deterministic pattern and the probability distribution of the outcomes remains the same regardless of the previous outcomes, that is $P_1(x_i) = P_2(x_i)$. In this case, the Shannon entropy stays constant, $H_1(X) = H_2(X)$, therefore $I = 0$ and the information gain is also zero. In layman terms, zero information means either no new data/results, or receiving random data/results; basically, either no news or conflicting news.