The communicational properties of single photons explain their strange behavior in the double-slit experiment

Mehran Shaghaghi
msa78@sfu.ca
University of Illinois-Chicago, Chicago 60612, IL, USA

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 paper, we explain this unique behavior by considering the communicational properties of the photons. Photons have three independently adjustable properties (energy, direction, and spin) that can be used to communicate messages. The double-slit experiment setup fixes two of these properties and confines the single photon's capacity for conveying messages to no more than one message. With such a low communication capacity, information theory dictates that measurements associated only with one proposition can obtain consistent results, and a second measurement associated with an independent proposition must necessarily lead to randomness. In the double-slit example, these are the wave or particle properties of the photon. The interpretation we offer is based on the formalism of information theory and does not make use of Heisenberg's uncertainty relation in any form.

I. 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] that is incompatible with the pattern of single particles that go through either of the slits. This leaves one to 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 the following feature, 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 to be the main point of demarcation between quantum and classical physics. Here, by taking into account that physical systems not only carry energy, momentum, etc. but also carry information, we propose an explanation for the limit on obtaining complementary information about the behavior of the single photons in the double-slit experiment.

II. The communicational properties of physical systems

Physical systems can store and deliver data through their adjustable properties. Routinely, we store our messages on a piece of paper using patterns of ink, or we use hard disk drives, which store data on directions of magnetization in a small region of their disks. In practice, any property of a physical system that can be adjusted can be used as a substrate to load a message upon. For example, a token with 8 possible colors –red, orange, yellow, green, blue, indigo, violet, and black– can be used to convey a message worth up to 3 bits of data through its color.

In the physical world, the messages are not necessarily stored in binary (0 or 1) states of the system, since the adjustable properties of the system can have more than just two states. Meaning, that unlike in the abstract world of mathematics where information is communicated bit by bit, in the physical world, messages can be communicated in various chunks of bits. For example, in the token case above, the message encoded in one of the 8 possible colors is conveyed in a 3-bit chunk. In general, the data storage capacity of an adjustable property of a physical system in bits is calculated by enumerating its number of states in base 2. Meaning, an adjustable property of a system with d states can carry a message worth up to $log_2(d)$ bits of data.

Here in this manuscript, we use the word *message* for what is conveyed in communication between the two ends. A message, or a piece of information, can be written in abstract form as a certain sequence of bits of data. The length of that sequence determines the bit value amount of the data contained in a message, e.g., “10011” is a 5-bit message. Thus, a message is composed of bits of data.

We define the *communication capacity* of a physical system as the total number of independent messages the system can communicate. For example, a token with 2 possible faces ("head" or "tail"), 8 possible colors, and 4 possible sizes to choose, can convey three independent messages: a 1-bit message using its face, a 3-bit message via its color, and finally a 2-bit message through its chosen size. As mentioned earlier, the adjustable properties of a system can be used to convey messages; therefore, the *communication capacity* of a physical system is determined by the number of its independently adjustable properties. The messages and pieces of information contained in a physical system are retrieved by performing appropriate physical measurements on each of the adjustable physical properties. The *data capacity* of the system, which is a mathematical concept, is determined by the number of possible states of the system. In our example, the total possible states of the token are 2×8×4=64, which leads to the total $log_2(64)=6$ bits of data capacity[1].

Generally, the capacity of the macroscopic physical systems for processing data, while bounded, is huge [9]. In particular, the number of messages that a physical system can communicate is limited to the number of adjustable properties it possesses. A macroscopic object, like a token, has a huge number of adjustable properties, such as mass, temperature, color, and width. In the microscopic realm however, many such attributes cease to exist in a well-defined or independent manner. Furthermore, microscopic physical systems have a much smaller number of components compared to macroscopic systems. Therefore, in general, microscopic systems have a much less number of independently adjustable properties, and accordingly, a much lower communication capacity. 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. Nevertheless, like in any other physical system, these attributes of the electrons can be used for the storage and transmission of messages.

III. Individual Photons and the double-slit experiment

Photons are physical systems with only a few numbers of adjustable attributes which makes their communication capacity very limited. Individual photons have only three independently

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[1] An adjustable property of a system can have continuous state space, and, *in principle*, the data that could be encoded in these spaces is unlimited. In other words, the messages that are carried by those properties can contain huge amounts of data. We refer the readers to appendix A for a discussion about the message carried by the system (physical information) *vs.* the information that can be inferred from the message (semantic information), in which the latter benefits from a wealth of shared background knowledge.

adjustable properties that may be used to convey messages: direction, frequency, and spin. These photon properties are all utilized in many 3D movie theatres using *'polarized 3D systems'* to convey the shape, color, and depth perception of the moving pictures. The cosmic microwave background (CMB) maps are also made by extracting these three pieces of information from the photons: direction (which way they were coming), frequency (energy), and spin (polarization) [10, 11].

Earlier, we mentioned the strange behavior of the single photons in the double-slit experiment. Performing a double-slit experiment requires certain arrangements, most importantly, the correct light source. To observe interference, it is crucial to use a coherent monochromatic beam of photons. In other words, all of the incoming photons must be highly directional –i.e., pointing to the same location– and must also have the same energies. Using a laser source provides a coherent beam of photons and has made demonstrating such experiments easily possible [12]. These prerequisites however, fix two out of three adjustable attributes of the photons and leave the photons in the double-slit experiment with only one non-fixed attribute (the spin). Thus the photons in the double-slit experiment are indeed physical systems with just a single adjustable attribute that would be able to convey absolutely no more than one message.

This account explains the nature of the unique behavior of the photons in the double-slit experiment and the reason why they cannot carry two independent pieces of information. The photons in the double-slit experiment are physical systems with only one adjustable attribute, and thus the communication capacity of just one message. On such a system, once a measurement is performed, a second measurement associated with any other independent proposition must necessarily contain an element of randomness. Randomness indicates that the measurement is performed on a system that has reached the state of zero information content (see Appendix B). This explains the observed randomness in the experiment when the observation of the complementary effects is forced. Furthermore, this indicates that such randomness is ontological and not removable.

IV. Discussion and 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 and convey messages. With this aspect of physical systems not unbounded, we found that in certain cases, such as photons in the double-slit experiment, the physical system can reach the lowest limit of communication capacity to convey just one piece of information. This leads to the impossibility of simultaneous reading of two independent pieces of information from the system.

While we'd like to confine our current discussion to explaining the behavior of the single photons in the double-slit experiment, a similar type of argument can be made for each of the macroscopic molecules in the meticulously prepared homogeneous beam of the macromolecule selected for performing the interference experiments with single large molecules [13, 14]. Such coherence experiments are not doable without a dynamical screening of the molecules in the preparation phase that puts a portion of the molecules in a coherent monochromatic beam [15], informationally isolated enough to exhibit some interference effects[2].

The unfamiliar case of single photons in the double-slit experiment is thus due to the unprecedented situation that involves performing measurements on a system that can convey absolutely not more than one message: one can perform an experiment to find out 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 a microscopic particle like a photon would not have a large capacity to simultaneously hold different pieces of information.

Our discussion of the photon's behavior in the double-slit experiment is based on the fact that every physical system is also associated with a communication capacity. It has not been unknown that physical systems can be used as communication devices or data storage [9]; however, it has not been pondered that some informational considerations could affect the

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[2] In these experiments, the presence of interference is inferred by observing whether the amplitude of the collected signal shows sinusoidal modulation that exceeds the experimental uncertainty, i.e., whether there is some interference effect besides classical expectation. One should note in these experiments, unlike the optical experiments that use highly coherent monochromatic beams, the signal minimum does not reach zero, i.e., there are molecules in the beam that behave classically.

behavior of physical systems. We argued that in the extreme case of reaching the lowest communication capacity, as in the case of the photons in the double-slit experiment, mathematics forbids obtaining two informationally distinct outcomes. Furthermore, reaching the bottommost limit of communication capacity, i.e., zero information, must necessarily contain an element of randomness, which is suggestive of quantum randomness.

The picture we presented in this paper, single photons as the physical systems with very limited communication capacity, can explain where the surprising behavior of the photons in the double-slit experiment comes from. 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.

Appendix A: 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 possible for example, to load three messages just on the different components of its momentum?

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

The following example can help show the difference: one may use a pulse of laser with adjustable wavelength –say with exact 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 can convey 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 with a wise choice of questions, one can thus transmit a wealth of information just by using a pulse of the laser. So it seems, that the wavelength of the 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 message that bears the information. In such encodings, the agents at the ends implicitly or explicitly benefit from myriads of shared background knowledge between themselves, e.g., they both know what is a wavelength, a *nm*, number bases, the choice of the questions, their order, etc., which none are part of the transmitted physical message.

Similarly, a single electron does not carry on itself per se the background knowledge of, for example, spatial directions, so that the observer at the receiving end would be able to project and read the momentum in specific directions. In practice, physical information is distinguishable only based on the distinctive physical properties of the message carrier. Meaning, that a single physical property with a huge number of states, physically only bears one message containing a big chunk of data equal to $\log_2(\#states)$ bits.

Appendix B: What does zero information mean in physics

Physically, we gain information from a physical object 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 data. Thus in the physical world, acquiring 'zero information' cannot be assumed to be equivalent to acquiring 'zero' data, but acquiring zero information means that the collected data represent zero information.

The information content of a message, composed of bits of data, can be evaluated mathematically. As we demonstrate, in the mathematical language of information theory, zero information means that the data 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

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

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 [16].

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's terms, zero information means either no new result or receiving random results; basically, either no news or conflicting news.

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