28 March 2025 · CC-BY 4.0

Qeios

Peer Review

Review of: "Aristotle, Heisenberg, and the Non-Locality and Non-Temporality of a Single Photon"

Harish Parthasarathy[1]

1. Netaji Subhas Inst of Technology, India

This work is an interesting qualitative contribution to our understanding of what it means to measure the properties of a photon, such as its trajectory, the intensity of a photon beam, its frequency, the set of frequencies in a bunch of photons, and the coherence time of photons. The author starts with the energy-time Heisenberg uncertainty relation and states that if the photon beam has several frequencies, say spread out over a band, then its coherence time would be very short. This is, of course, a basic property of the Fourier transform since energy and time are Fourier-related pairs, and it is a mathematical theorem due to Weyl that if the wave function in the space of one variable gives a magnitude square having a given dispersion, then the wave function in the Fourier-transformed variable space will have a magnitude square that will have a dispersion that is inversely proportional to that of the former. In particular, the Fourier transform of the Dirac delta function is unity, so if the coherence time is zero, then the energy/frequency spread of the photons would be infinite and vice versa. After this, the author goes on to discuss how the trajectory of a photon is measured.

Actually, the trajectory of any quantum particle cannot be measured generally at different times because the time evolution of an observable in quantum mechanics does not generally commute at different times, and hence joint measurability at two or more times is impossible as it is subject to Heisenberg uncertainty. Moreover, one seldom talks about the trajectory evolution of a quantum particle; one only talks about the wave function/state evolution of the particle with time. When measurements are taken on the evolving state at one time, then the future states get affected in view of the state collapse postulate following the measurement. However, nowadays, many physicists, including the great Roger Penrose, believe that it is the idea of measurement on a quantum system that makes quantum mechanics, as we understand it, an incomplete theory because although state evolution is reversible, the process of

doi.org/10.32388/NHNI76

measurement is irreversible owing to state collapse, and to make a measurement, we must step out of the system and measure it, so the measurement apparatus is not a part of the quantum system. It is rather a classical system. For quantum mechanics to be consistent, the measuring apparatus must be a part of the quantum system, but then it would have to measure itself also, which is impossible.

The author mentions some interesting ideas of Aristotle that are even today valid in quantum mechanics. One of these ideas deals with whether reality exists prior to measurement and whether this reality can be exactly determined without perturbing it.

The present view of quantum mechanics gives a negative answer to this question.

Another fact related to trajectory measurement is connected with the Feynman path integral approach to quantum mechanics, namely, the probability amplitude for a particle to be at a certain point in space at a given time is obtained by summing a phase factor over all the trajectories of the particle up to the given time. This means that the particle has somehow learnt about all the possible trajectories up to the present time that finish at the given point. But how can it do so without actually going back to the past and going along another trajectory? Another point worth noting is that when a quantum particle/system is coupled to a noisy bath, then the system state evolution is no longer unitary. It is described by a quantum dynamical semigroup, i.e., a semigroup in time of TPCP maps on the state. Unitary evolution preserves entropy, but TPCP maps do not. According to the second law of thermodynamics, the rate of entropy increase must be positive or zero. This means that only those couplings of the system to the bath (We assume the bath to be outside our universe) are permissible that are in agreement with the second law of thermodynamics. Thus, nature somehow chooses the right couplings. Finally, according to the wave theory of light, i.e., according to Maxwell's equations, as the author has pointed out, the photon wave travels at the speed of light, which means that there is a delay in the transmission of information if we choose to use photons for communication. On the other hand, when the transmitter and receiver have entangled states, as per the EPR paper, communication with photons can take place at infinite speed. Thus, quantum mechanical methods can be used to violate the rules of classical wave theories. This suggests that a careful analysis must be made of any problem dealing with photons, namely, whether we are using classical or quantum mechanical analysis. Generally, when the number of photons is very large, we use classical wave theory with a good approximation, and when it is very small, we use the quantum theory based on the algebra of pure and mixed states and operators.

Photon trajectories cannot be measured at one stroke; first, we measure the photon position at time t_1, then we allow the photon to move and measure it at time t_2 > t_1, and so on. After each measurement, the photon trajectory gets disturbed in view of the Heisenberg uncertainty, and hence accurate determination of the trajectory becomes impossible.

If X(t) and Y(t) are respectively the position and momentum of the photon at time t, Heisenberg uncertainty prevents measurement of both X(t) and Y(t) at a fixed t. However, it can happen that the X(t)'s commute at different times, and then the photon position trajectory alone can be measured. However, if the Hamiltonian is the sum of its kinetic and potential energies, with the kinetic energy being a function of momentum and the potential a function of position, then denoting by U(t) the unitary evolution according to this Hamiltonian, X(t_2) = U(t_2 - t_1)^*X(t_1)U(t_2 - t_1) shows that X(t_1) and X(t_2) will not commute, and hence in this case, the photon position trajectory cannot be measured. On the other hand, if the total energy is only kinetic and therefore a function of momentum alone, then the momentum trajectory at different times will commute, and hence the momentum trajectory can be measured.

The key to comparing classical and quantum mechanical results is the Wigner distribution, which is a complex-valued distribution in phase space that well approximates what we call the joint probability density in classical theory, the error being proportional to Planck's constant cube, which defines the phase volume of a cell in which one particle is present.

Nonlocality means that measuring the exact time of an event is not possible, the error being spread out over a time interval. Non-temporality could mean localization in time, but that would mean nonlocalization in frequency because time and frequency are Fourier pairs.

Aristotle's ideas are relevant in modern quantum mechanics precisely because of Feynman's path integral approach. The particle beforehand knows about the phase factor exp(iS/h) along every path leading to the final point without having to traverse each path. This is in agreement with Aristotle's philosophy that reality exists before anybody has observed it and that what we observe about reality is really a distorted version, as it is in quantum mechanics, which states that without disturbing the system, we cannot get to know what is inside it.

Declarations

Potential competing interests: No potential competing interests to declare.