Research Highlight

What is the wave function in quantum mechanics?

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Quantum mechanics, a pillar of modern science and technology, has benefited human society for a century. Quantum mechanics works well, its predictions agree amazingly well with experiments, and its mathematical structure is beautiful. However, the debate on the meaning of quantum mechanics has remained a hot topic to date. In the past 100 years, what most people did was “Shut up and calculate”, and wave functions always gave us a correct probability list of measurement outcomes.

There are a few interpretations of the wave function in quantum mechanics, for instance the traditional and dominating Copenhagen interpretation, the De Broglie's pilot wave interpretation, and many-world interpretation, the realistic interpretation and so on [1]. In the Copenhagen interpretation, the wave functions are supposed to only provide knowledge of phenomena, and what is observed certainly exists, and what is not observed are still free for people to make assumptions. Einstein insisted that physics should look for “really existing objects”. In his famous paper on EPR paradox [2], he proposed the EPR paradox and argued that there would be more than one element of reality in quantum mechanics when entanglement was involved, and he concluded that quantum mechanics was not a complete theory. In Ref. [3] or early in Ref. [4], the “REIN” realistic interpretation states that the wave function is the way quantum system exists, namely microscopic particle is an extended body as the wave function, the quantum “cloud”, occupies in space, and with both amplitude and phase. The wave function moves at a speed less than or equals to the speed of light. When the wave function is measured, the quantum “cloud”, collapses and exhibits the particle nature. This particle-wave duality property has been exploited to perform duality quantum computing where linear combinations of unitary operations are allowed, in contrast to traditional quantum algorithms such as Shor and Grover/Long algorithm where only product of unitary operations are permitted. An encounter delayed choice experiment was proposed and demonstrated [3]. In the encounter delayed choice experiment, the wave functions from both arms of the Mach-Zehnder interferometer encounter at the second the beamsplitter at the exit, and the second beamsplitter is inserted in the middle of the encounter, and the front parts (before beamsplitter insertion) of the wave functions exhibit particle nature, and latter parts (after the beamsplitter insertion) exhibit wave nature.

In a recent work, Zhou et al. from Harbin University of Science and Technology and University of Science and Technology of China performed a quantum twisted double-slit experiment to address this long-standing issue of the nature of wave function [5]. Photonics orbital angular momentum (OAM) and its group velocity slowing-down feature [6,7] are employed to provide an interface for extracting photons’ propagation history. Specifically, the wave functions of photons diffracted from the twisted double slits is in a superposition state $|\psi(0) + \beta\psi(1)|$, and then are selectively measured (observed) in |0⟩. Now, consider two either-or cases: (1) If the photon behaves as neither a particle nor a wave prior to the measurement and the propagation history is formed by the state what we observed. There shall be no arrival delay because the propagation history is formed by |0⟩ state; (2) If the nature of the photon is pre-existing before the measurement (collapse), the arrival delay consisting with the theoretical prediction calculated from its wave function $|\psi(0) + \beta\psi(1)|$ will emerge, because the propagation history had been formed by its wave function before the measurement.

The result obtained from the experiment is that there is a delay between the twisted wave part and the one without twist. This tells us that the nature of the photon prior to the measurement is pre-existing—in a form of its wave function! That is to say, the individual photon travels along both paths (as a quantum “cloud”) after passing the double slits.

This work has significant impact—added another proof that wave functions are real. It also touches many fundamental issues. For instance, there is an interesting relationship between the debate of wave functions’ physical reality and the reversibility paradox. The results revealed in this work—wave function is real—will change people’s way of looking at quantum mechanics in fundamental layer. Many fundamental issues will be aroused, for instance how to understand the entanglement between multiple particles? Is it a “spooky action at a distance” or a fact that every particle exists in multiple locations simultaneously? If collapses break the T-symmetry and define the arrow of time, how to understand space-time in quantum theory?
Conflict of interest

The author declares that he has no conflict of interest.

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1 Also see arXiv:quant-ph/0512120. It was briefly mentioned in an abstract (5111-53) (Tracking No. FN03-FN02-32) submitted to SPIE conference “Fluctuations and Noise in Photonics and Quantum Optics” in 18 Oct 2002.