Quantum control and foundational experiments

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The wave-particle duality dates back to the contract between de Broglie's matter waves and Einstein's quanta of light. Consistency with the modern quantum-mechanical description still left open the possibility that quantum systems always behave either definitely as a particle or definitely as a wave, potentially adopting to specific experimental situation [1]. A systematic introduction of such models can be done using hidden variables [2]. This is precisely what is tried to be excluded in Wheeler's delayed-choice experiments, in which the observer chooses to reveal the particle or wave character of a quantum system, such as at a late stage of the experiment.

Incorporating the quantum behavior of the controlling devices in such experiments (and quantum-information technology and toos of analysis) allows for quantum-controlled experiments and specifically for a quantum version of Wheeler's delayed-choice experiment [2]. Using a quantum control has several consequences. It enables us to measure complementary phenomena with a single experimental setup and shows that a photon can have a morphing behavior between particle and wave. It allows to dispense with the delay lines and introduce tabletop realizations of the experiment.

Various configurations of the quantum delayed choice experiment showed that the hidden variable models for its description are self-contradictory [1]. Controlling the wave-particle test of property of single photons with quantum entanglement [3], while being a bad test of Bell-type inequalities reveals that the very formulation of a priori defined wave and particle properties becomes internally inconsistent.

[1] X.-S. Ma, J. Kofler, and A. Zeilinger, *Delayed-choice gedanken experiments and their realizations*, Rev. Mod. Phys. **88** 015005 (2016).

[2] R. Ionicioiu and D. R. Terno, *A proposal for quantum delayed-choice experiment*, Physical Review Letters **107**, 230406 (2011).

[3] K. Wang, D. R. Terno, Č. Brukner, S. Zhu, and X.-S. Ma, *Controlling wave–particle duality with quantum entanglement*, arXiv: 2112.11659 (2021).