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Experimental confirmation of wave-particle duality

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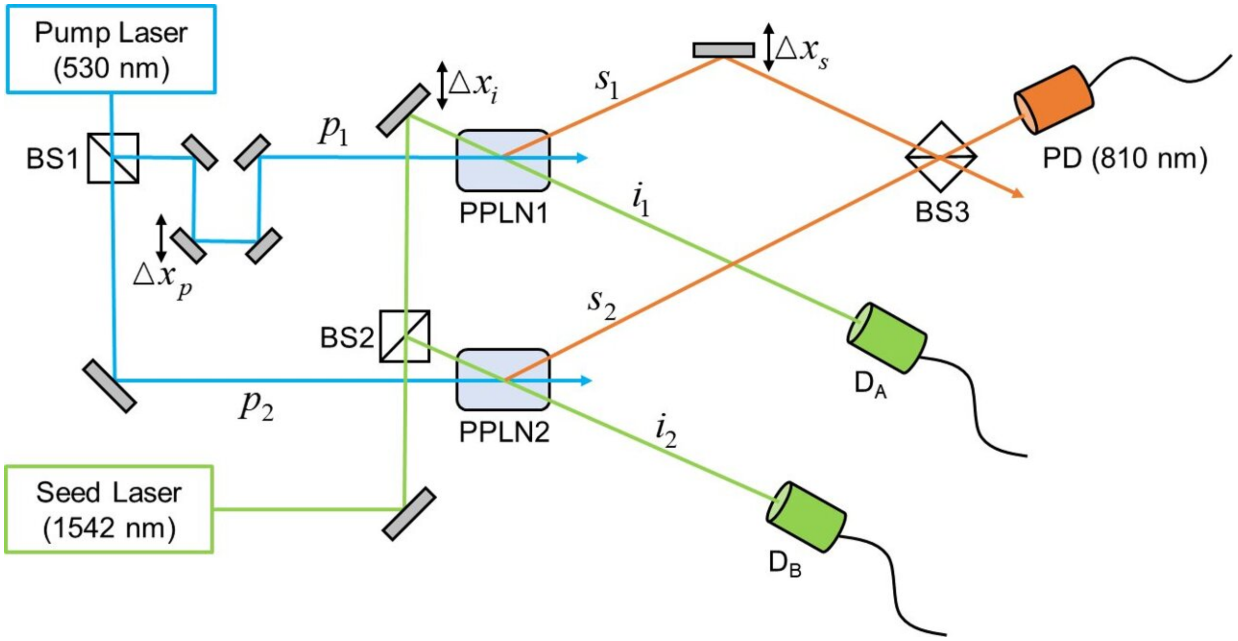
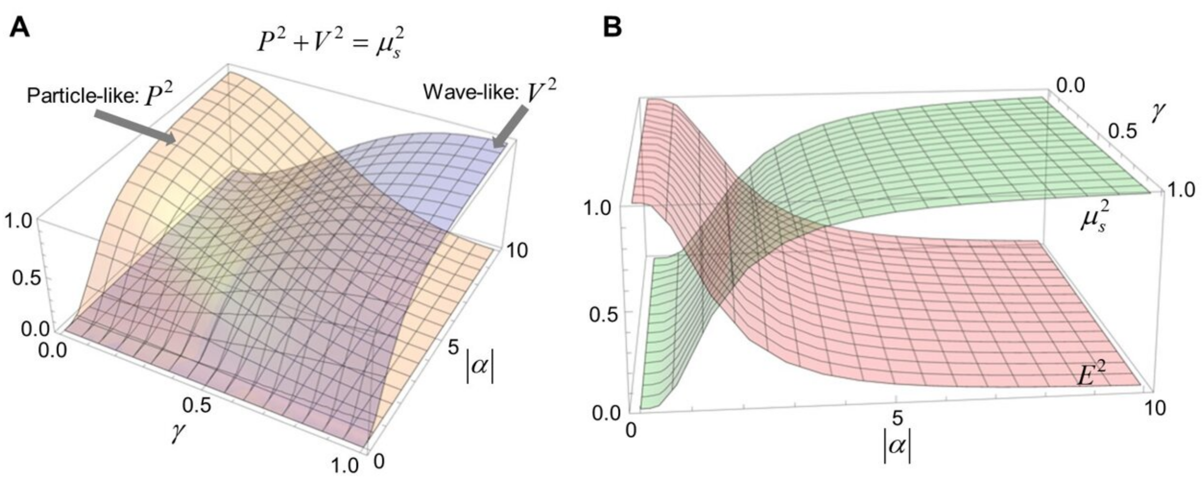


Two SPDC crystals, PPLN1 and PPLN2, are pumped and seeded simultaneously by the same pump and seed coherent lasers, respectively, resulting in the emission of two signal photons s1 or s2 for quantum interference detection at PD. Then, conjugate idler photons i1 and i2 provide the which-path (or which-source) information, where the controllable source purity is determined by the overlap between the SPACS of one of the idler modes and the unchanged coherent state of another idler mode. Two idler fields can be detected independently by detectors DA and DB. Credit: Institute for Basic Science

The 21st century has undoubtedly been the era of quantum science. Quantum mechanics was born in the early 20th century and has been used to develop unprecedented technologies which include quantum information, quantum communication, quantum metrology, quantum imaging, and quantum sensing. However, in quantum science, there are still unresolved and even inapprehensible issues like wave-particle duality and complementarity, superposition of wave functions, wave function collapse after quantum measurement, wave function entanglement of the composite wave function, etc.

To test the fundamental principle of wave-particle duality and complementarity quantitatively, a quantum composite system that can be controlled by experimental parameters is needed. So far, there have been several theoretical proposals after Neils Bohr introduced the concept of "complementarity" in 1928, but only a few ideas have been tested experimentally, with them detecting interference patterns with low visibility. Thus, the concept of complementarity and wave-particle duality still remains elusive and has not been fully confirmed experimentally yet.

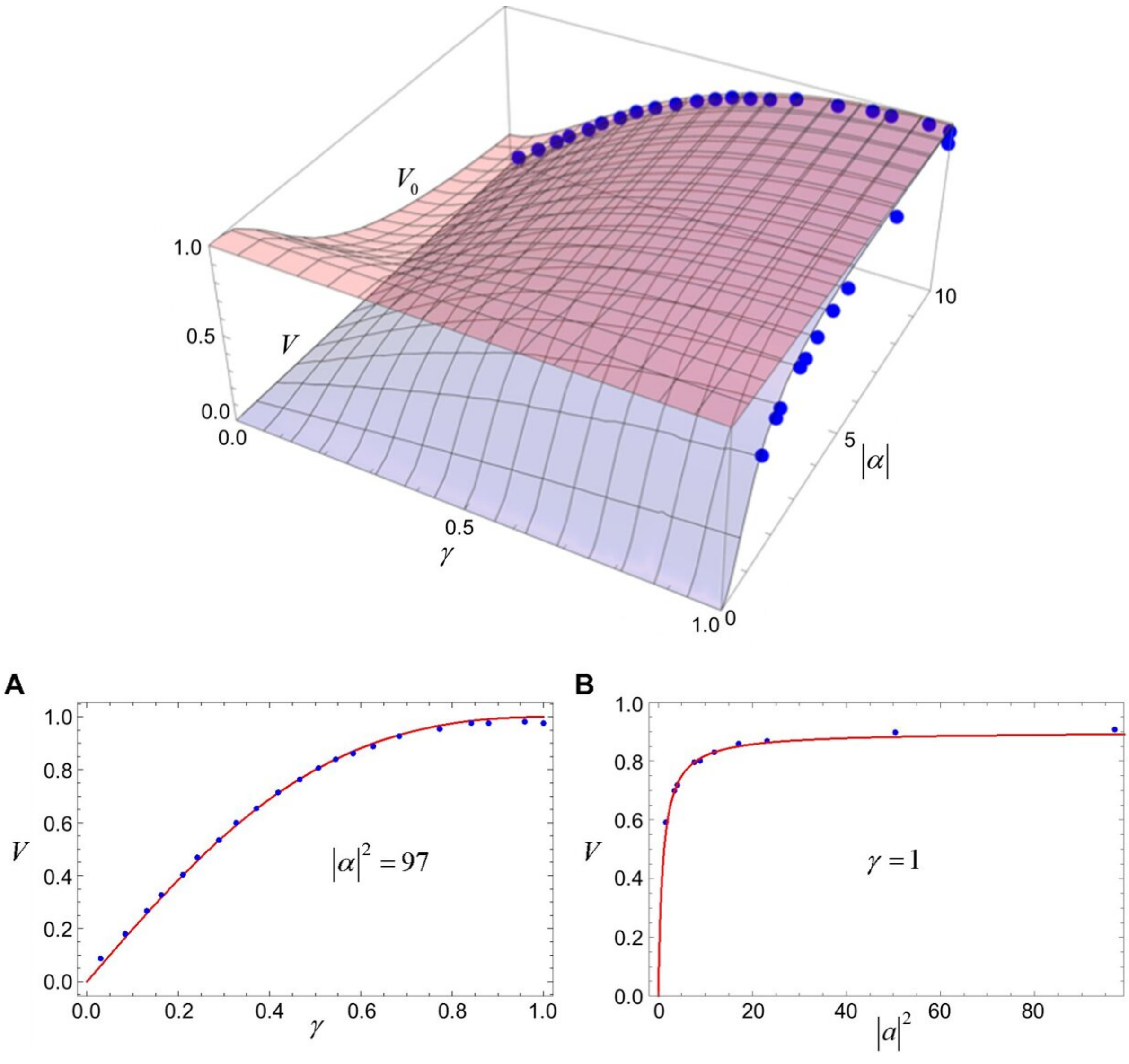
To address this issue, a research team from the Institute for Basic Science (IBS, South Korea) constructed a double-path interferometer consisting of two parametric downconversion crystals seeded by coherent idler fields, which is shown in Figure1. The device generates coherent signal photons (quantons) that are used for quantum interference measurement. The quantons then travel down two separate paths before reaching the detector. The conjugate idler fields are used for extracting path information with controllable fidelity, which is useful for quantitatively elucidating the complementarity.



(A) Quantitative complementarity relation P2 + V2 = μs2 with respect with respect to γ = |α2| / |α1| and |α| = |α2|. Here, path predictability P represents particle-like behavior, while fringe visibility V represents wave-like behavior of the quanton in the double-path interferometer. The totality of complementarity is bounded by the source purity. (B) Source purity μs of the quanton (signal photon) and entanglement E between the quanton and which-path (which-source) detector form another complementarity relation μs2 + E2 = 1. These two measures are plotted with respect to γ = |α2| / |α1| and |α| = |α2|. Credit: Institute for Basic Science

In a real experiment, the source of quantons is not pure due to its entanglement with the remaining degrees of freedom. However, the quanton source purity is tightly bounded by the entanglement between the generated quantons and all the other remaining degrees of freedom by the relation $\mu_s = \surd(1—E^2)$, which the researchers confirmed experimentally.

The wave-particle duality and the quantitative complementarity $P^2 + V^2 = \mu_s{}^2$ (P, a priori predictability; V, visibility) were analyzed and tested using this entangled nonlinear bi-photon source (ENBS) system, where the superposition states of the quantons are quantum mechanically entangled with conjugate idler states in a controllable manner. It was shown that *a priori* predictability, visibility, entanglement (thus, source purity, and fidelity in our ENBS model) strictly depend on the seed beam photon numbers. This points to the potential application of this approach for the preparation of distant entangled photon states.



Blue points are experimental data taken from the team's recent paper. Experimental data coincide with the visibility V, not a priori visibility V0 across the whole ranges of γ and $|\alpha|$. This plot validates the team's analysis of the ENBS experimental results in terms of the wave-particle duality and quantitative complementarity relations. Credit: Institute for Basic Science

Richard Feynman once stated that solving the puzzle of quantum mechanics lies in the understanding of the double-slit experiment. It is anticipated that the interpretation based on the double-path interferometry experiments with ENBS will have fundamental implications for better understanding the principle of complementarity and the wave-particle duality relation quantitatively.

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Provided by Institute for Basic Science

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