Abstract

Quantum mechanics continues to challenge our intuitions about reality and information, while offering powerful new tools for communication and security. This thesis explores the interplay between fundamental quantum principles and their operational consequences, weaving together three interrelated threads: device-independent cryptography, semi-device-independent interferometry, and the nature of wave-particle complementarity.

We begin by examining the principle of information causality. Originally proposed to capture the limits of quantum nonlocality without relying on the full formalism of quantum theory, information causality provides profound insights into the security of quantum communication. We show that a multipartite formulation of this principle naturally leads to strong monogamy relations for the violation of Bell inequalities. These relations guarantee the security of device-independent quantum key distribution against individual attacks, even from a potentially post-quantum eavesdropper. In contrast, the simpler bipartite formulation fails to provide such guarantees, highlighting the essential role of multipartite correlations.

Building on this, we investigate wave-particle duality in a semi-device-independent framework. By connecting complementary interferometric quantities, namely visibility and input distinguishability, to entropic measures with direct operational meaning, we develop a method to certify quantum behaviour and security from observable interference patterns. Applying symmetry conditions and exploring tunable interferometers, we identify scenarios where classical bounds are violated and secure communication can be established. These theoretical insights are confirmed through a proof-of-principle experiment using orbital-angular-momentum encoded photons, and an improved security bound expands the parameter region for a reliable semi-device-independent certification.

Finally, we turn to the foundations of quantum realism through delayed-choice experiments. By modifying the causal structure and introducing entanglement-assisted control, we trace how wave and particle properties emerge throughout the interferometer. Using a contextual realism quantifier, we show that the assignment of wave or particle characteristics depends sensitively on the causal order and the available information, even when the final interference visibility remains unchanged.

Together, these investigations illuminate the deep connections between quantum correlations, operational constraints, and the nature of reality. They demonstrate how principles such as information causality and semi-device-independent security are rooted in fundamental features of quantum mechanics, and how causal and contextual structures shape the expression of wave-particle complementarity. This work bridges theory and experiment, offering a richer understanding of both the operational and the conceptual aspects of the quantum world.