Abstract

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Measurements are a fundamental cornerstone of physics, and in quantum science they play a uniquely central role from both foundational and technological perspectives. It is through measurements that we interact with nature: the way we probe a system determines which properties become accessible, and how they can subsequently be exploited. In quantum mechanics (QM), a measurement is not merely a passive readout of a pre-existing property; it is an active process that, through unavoidable back-action, can shape the very phenomena observed and change the state of the system. From a metrological perspective, the emphasis thus shifts to how measurements are implemented and performed, so that quantum states and correlations can be characterized, verified, and ultimately exploited in ways that are both minimally invasive and practically useful across platforms and networked scenarios.

In this work, we take this need as our guiding objective: to turn the study of quantum measurements and resources into concrete, reproducible methods enabling access, characterization and protection of quantum states under realistic conditions.

After a brief introduction on QM and related quantum technologies (Chapter 1), Chapter 2 presents a weak measurement (WM) scheme to perform multiple noncommuting measurements on entangled systems without altering their state, a task usually forbidden by the traditional quantum measurement paradigms. A WM is a low-intensity interaction between a quantum system and a measuring device, allowing to extract limited information while keeping the state largely intact. We exploit this property of WMs to realize the first estimation of the entire Bell parameter on a single entangled-photon pair, a task intrinsically forbidden in traditional (projective) quantum measurement frameworks, opening new paths in the field of quantum state estimation. Then, with the same method, we perform the first experimental test of the recently-introduced Relativistic Independence principle, showing how the measurement choice can limit the access to local and nonlocal correlations, demonstrating an interplay and balance between the two. Moreover, we illustrate that, with this scheme, one can access the outcome probabilities for the full set of observables in a Bell test, showing that some probabilities can become intrinsically negative. These works defy traditional, textbook QM paradigms, showing that quantum correlations can be estimated almost

non-invasively by calibrating information gain and back-action in the weak regime, providing the operational tools to quantitatively address the balance between local and nonlocal correlations.

In Chapter 3 we investigate single-photon entanglement, focusing on the path-entangled state of a single photon delocalized over two spatial modes. To make such states measurable and certifiable in a network, we introduce a verification technique that leverages a genuinely nonlocal interference effect between single photons, coordinated by a dedicated node, dubbed "verifier" and represented by metrological institutes, furnishing standardized path-entangled single photons to the network. Within this architecture, we devise a protocol to reconstruct unknown path-entangled states, allowing to certify entanglement distributed across the network.

Finally, in Chapter 4 we address decoherence in quantum channels and introduce the Qubit Universal Protection (QUP) protocol, a protection scheme for quantum states that is independent of both the input state and the particular decoherence effect. QUP exploits a decoherence-free ancillary degree of freedom together with Quantum Zeno–based protection to suppress decoherence without prior knowledge of the channel or the state to be protected. We demonstrate the protocol on single-photon polarization states, benchmarking QUP-assisted transmission against an unprotected one to assess performances. In principle, QUP can protect arbitrary quantum states, including entangled ones, with a potential impact across quantum-technology platforms.

In conclusion, in this thesis we investigate key traits of QM like the concepts of measurement, entanglement, and decoherence, advancing their understanding. By developing new measurement protocols and techniques relevant to real technology-related implementations, both on a theoretical and experimental level, we contribute to the progress of the emerging quantum technologies and, in particular, of the field of quantum metrology.