Doctoral Dissertation
Doctoral Program in Metrology (33.th cycle)

Developing new paradigms for quantum measurements

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Summary

Ever since its inception in the early 20^{th} century, Quantum Mechanics has led to the development of many groundbreaking technologies, such as lasers, semiconductors, and so on. These technologies, which relied on general ensemble properties of quantum systems, are usually referred to as part of the "first quantum revolution". Today, a second quantum revolution, based on specific properties of single quantum systems, is underway, and more and more technologies able to generate and manipulate individual quantum states (and exploit their peculiar quantum properties) are being developed. One of the applications of these new technologies are quantum metrology and sensing which exploit quantum effects to overcome the limits of classical systems, achieving higher precisions and better signal-to-noise ratios in several measurement scenarios. For this reason, the development of new standards and procedures for the characterization of these new quantum technologies, as well as the development new quantum-enhanced measurement protocols, are fundamental tasks for quantum metrology.

In my thesis, I tackle both tasks for single/few photons systems, presenting several works which focus on state characterization and the development of novel quantum parameter estimation techniques and quantum measurement protocols, presenting in each case the theoretical framework together with the experimental results obtained in the practical implementation. The experiments have been performed exploiting quantum optics setups able to generate, manipulate and detect single- and entangled-photon states.

The first two works I present are aimed at characterizing single- and entangled-photon sources. The first work in this context the development of a strategy to estimate the multi-photon component of a continuous wave heralded single-photon source, paving the way for a standardization of the characterization of single-photon sources as one of the key tools of several quantum technologies, some of them even already stepping foot on the market (e.g. quantum cryptography). The strategy has been successfully applied in a pilot comparison among a few European national metrological institutes (INRiM, NPL and PTB).

The second work, instead, concerns the optimal estimation of the amount of non-classical correlations (i.e. discord and entanglement) within a specific class of two-photons states, for which I introduce and test experimentally some optimal unbiased estimators for the aforementioned quantities. There, I show how such estimators perform better than their nonoptimal counterparts by allowing to achieve the minimum uncertainty possible, i.e. the one granted by the saturation of the Quantum Cramér-Rao bound.

Then, I present two works in which I investigate new quantum measurement paradigms based on weak measurements, and their possible applications to quantum metrology and other quantum technologies. The first protocol, protective measurement (PM), allows extracting the expectation value of a quantum observable even from a single detection event, something apparently in sharp contrast with the very definition of expectation value as a statistical quantity associated with an ensemble of particles. I show the first experimental implementation of such protocol, involving a single-photon-based quantum optics setup. I also analyse the statistical uncertainties of PM, showing the advantage it grants with respect to "strong" (projective) measurements. Second, I illustrate the theory and the first experimental implementation of robust weak measurement (RWM), an evolution of PM. With RWMs one can obtain a reliable estimate of the weak value of an observable with just a single detection event, instead of averaging over multiple events like for usual weak value measurements.

Finally, I present the first experimental reconstruction of a pseudo-density operator (a generalization of the usual density operator), a novel quantum mechanical tool able to describe temporal and spatial correlations on the same level. Such formalism is able to provide a satisfactory description of quantum systems even in situations with which the usual density operator formalism of quantum mechanics can present some issues, and even give rise to paradoxes . As emblematic examples, we consider its application to the optical simulation of two physical scenarios: entangled particles entering an open time-like curve, and black-hole evaporation.

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