Abstract

Understanding both the practical and fundamental limitations on the generation and observation of strictly quantum effects constitutes a key challenge in modern physics and in the development of modern quantum technologies. Correlations between the outcomes of measurements performed on individual quantum systems can reveal the presence of such effects and enable the characterisation of their properties. Numerous studies conducted since the second half of the twentieth century have produced significant results concerning the detection of quantum entanglement and the violation of Bell inequalities. With the advancement of quantum technologies and the consolidation of quantum information theory, researchers have increasingly focused on the physical constraints governing the generation and observation of quantum correlations.

This dissertation is devoted to the analysis of these issues from several complementary perspectives. The first one concerns the limitations imposed by the finite number of state copies available in an experiment. This problem is particularly relevant for multiphoton states generated via spontaneous parametric down conversion, where low coincidence rates make it difficult to obtain large measurement statistics within a short time. A similar issue arises when testing Bell inequalities while accounting for all possible measurement outcomes, including cases in which no detection event occurs. Combining this approach with the constraints resulting from the lack of calibration between separated reference frames enables the analysis of more experimentally friendly scenarios of Bell inequalities violation based on random measurements. The notion of a reference frame in quantum mechanics can be extended by associating it with a specific quantum particle, forming a so-called quantum reference frame. Since such a frame can be correlated with other particles in the composite system, analysing changes in entanglement and superposition under transformations between the quantum reference frames becomes an important problem. Another topic explored in this work concerns the possibility of observing Bell inequalities violations simultaneously across several overlapping subsystems. While this phenomenon is impossible for three-particle systems with two measurement settings per party, it becomes feasible in multi-particle systems. All of the aforementioned scenarios address the limitations in observing strictly quantum correlations. However, it should be emphasised that before such correlations can be analysed, the appropriate quantum states must first be generated. An additional issue discussed in this dissertation concerns the speed at which strongly entangled quantum states can be produced through two-body interactions. A natural extension of this idea is the investigation of higher-order interactions verification that may accelerate this process. Each of the described problems contributes to this dissertation, which consists of a series of six publications.