Abstract

The discovery of the quantum behavior of small-scale systems resulted in a plethora of fundamental questions about the nature of our world. It also provided new avenues for the development of technologies that utilize quantum phenomena. Therefore, the study of non-classical phenomena became one of the core subjects in physics. With an increasing understanding of simple systems containing a small and fixed number of particles, the problems of more complex systems gain increasing attention, both from the point of view of more complex applications and the fundamental question of when quantum effects play an important role. This motivates studies of quantum fields in states of undefined particle numbers in which quantum features still play an important role.

This PhD dissertation summarizes a series of papers, coauthored by the PhD candidate, concentrated on describing non-classical phenomena in bosonic systems containing an undefined number of particles, especially in the regime of high average numbers of particles.

The first article "Simplified quantum optical Stokes observables and Bell's theorem" describes new observables that allow for the detection of Bell non-classicality of polarization-entangled states with an undefined number of photons. In particular, the proposed measurement scheme enables detection of non-classicality in the range of average number of photons that greatly exceeds previous approaches. These observables can be realized with any intensity measurement for which the response of the apparatus increases with the number of photons. This is because they are constructed as a sign of the difference in the response of the detectors detecting photons in two orthogonal polarization modes.

The second article "Bosonic fields in states with undefined particle numbers possess detectable non-contextuality features, plus more" presents a new representation of $\mathfrak{su}(2)$ algebra on a two-mode bosonic Fock space. The resulting set of operators enabled us to propose a generalized Peres-Mermin square, and thus to describe non-classical effects of contextuality for bosonic fields with an undefined number of particles. What is more, the effect becomes a common feature of states with a high number of particles, reaching quantum bounds for the used criterion in the limits of macroscopic average numbers of particles; a behavior which is rare in considerations of quantum phenomena.

The third article in the series "Generalization of Gisin's Theorem to Quantum Fields" concerns the problem of Gisin's theorem in the context of quantum fields. Our generalization states that any pure entangled state of a quantum field violates some Bell inequality. Thus, Bell non-classicality within the framework of quantum field theory is present in pure states of all entangled systems even when the number of particles is undefined;

The last paper "Open dynamics of entanglement in mesoscopic bosonic systems" proposes a mesoscopic description of bosonic fields that allows considerations of the open evolution of discrete variable entanglement. Mesoscopic descriptions aim to simplify different problems by considering only the most important degrees of freedom. The proposed description is based on the correlations in particle numbers. With these correlations, we build the extension of the recently proposed reduced state of the field formalism, which, however, by itself does not contain information about entanglement. Our formalism mathematically resembles the first quantization Hilbert space of two particles and therefore allows for the intuitive use of already known tools of quantum mechanics. We show that it is able to describe the entanglement of both Gaussian and non-Gaussian states. In addition, this formalism is not limited to describing entanglement. As an example for this, we consider how the non-classical effect of sub-Poissonian statistics is transformed into entanglement through the action of the beamsplitter.