“Collisional properties and many body effects in ultracold systems. Quantum interferometry.”

PhD dissertation abstract

In a growing number of experiments, many-body entangled states are created and employed to surpass the shot-noise limit in atom interferometry. The precision is bounded by this limiting value whenever the particles exhibit only classical correlations. However, with a proper choice of the state which is injected into the interferometer, this limit can be overcome. Thus, a certain class of non-classically correlated states is useful for precise metrology.

The main objective of this thesis is to show that the indistinguishability of bosons is a resource that can be employed for ultra-precise interferometry. To support this idea, two systems are considered, where useful quantum correlations arise solely from the indistinguishability of the constituent bosons. The first example is a system, in which pairs of identical particles are scattered from a Bose-Einstein condensate into two well-separated regions, which are later identified with the two arms of an interferometer. In the second case, the interferometer is fed with two independently prepared Bose-Einstein condensates correlated only due to the indistinguishability.

The analysis of these systems is founded on the concept that some entangled states are highly susceptible to interferometric transformations. As is shown, this statement can be precisely quantified using measures of the distinguishability of the probability distributions characterizing those states.

In the course of discussion, the object known as the Fisher information naturally emerges as the quantity unifying all the presented measures. In other words, it is the Fisher information that describes the susceptibility of the state to an interferometric transformation. Moreover, the theorem known as the Cramér-Rao lower bound constitutes the bridge between the distinguishability of states and metrology.

In the next step, a theorem is presented which relates the Fisher information with non-classical correlations. The consequence of this statement is that the sub-shot-noise sensitivity of interferometric phase estimation is a signature of non-classical correlations.

Before injecting a many-body state into the interferometer, one should make sure if this state is usefully entangled. Therefore, it would be helpful to have a simple criterion for entanglement that would signify potential usefulness of the state. In this thesis, such a criterion is provided which is based on the Cauchy-Schwarz inequality. It applies to the system of bosons, which do not possess coherences between different number states.

After setting the theoretical framework, specific experimental scenarios are considered. First, a question is asked whether a collision of two Bose-Einstein condensates can lead to creation of entangled atomic pairs. It is shown that the detailed setup of the collision leads to effects

that are destructive for generating entanglement useful for metrology. Therefore, a different scheme is necessary which would be free of such phenomena.

In the main part of the thesis, a theory is developed, which describes the scattering of atomic pairs from a condensate into two disjointed zones. It is shown, that, contrary to the previous case, the system consists of highly entangled pairs useful for ultra-precise sub-shot-noise interferometry. Moreover, since the Cauchy-Schwarz inequality is violated in this system, the presence of entanglement can be easily verified. This theory is then applied to characterise the realistic case of the twin-atom beam experiment.

Finally, an interferometric scenario is considered in which the initial state consists of two independently prepared Bose-Einstein condensates. It is shown, that, when this state is taken as the input of an interferometer, the device can operate below the shot-noise limit. The conditions for this to happen are presented, together with the scheme of the interferometric phase estimation, such that could benefit from these non-classical correlations. The proposed scheme circumvents the difficult stage of the entangled state preparation. The only condition, which is required, is to have a precise control over the distribution of the total number of atoms in each atomic cloud.

Through this thesis, the link between the state susceptibility to the change and the entanglement is thoroughly exploited. Here, the high susceptibility of states, quantified by the Fisher information, is considered as a potential resource for ultra-precise metrology. Nevertheless, the underlying principle adopted in the thesis may also be applied in other areas of physics.