Description for general public

On the popular level, Quantum Mechanics, thanks to its famous Heisenberg uncertainty relation, is perceived as a theory preventing physical quantities of quantum systems to be measured precisely. Quantum Metrology goes against this intution, and aims to demonstrate that in reality appropriate use of ubiquitous features of quantum systems may allow to perform ultra-precise measurements with performance going beyond that which is achievable when light and matter are treated classically.

The basic technique utilized in Quantum Metrology is interferometry. Irrespectively of whether we deal with atoms or light, interferometry amounts to preparations of a physical system in a superposition of two states (e.g. two paths that a photon or an atom travels or two internal states of an atom), evolution of the system in a way dependent on the parameter to be measured and eventually the measurement. The simplest example is an optical Mach-Zehnder interferometer, where photons find themselves in a superposition of being in two arms of the interferometer carrying information about the difference of optical lengths of interferometer arms.

The most spectacular example of a practical application of Quantum Metrology ideas is modification of the standard optical interferometric scheme, where every photon interferes only with itself, to the situation where there are unique quantum correlations between the photons, called quantum entanglement, causing the photons to interfere in a collective way and as a result increasing the sensitivity of the device.

This idea is at this very moment under implementation in the famous LIGO gravitational wave detector, which is in fact a huge optical interferometer designed to detect minute changes in the length of its arms, which may be caused by a passing gravitational wave. It is expected that thanks to the use of quantum entanglement it will be possible to increase the sensitivity of the device by at least a factor of two without the need to increase the laser power.

This project focuses on development of theoretical tools of quantum metrology, which will allow for a more precise quantitative description of more complex situations encountered in applications such as magnetometry, gravitometry based on cold atom or Bose-Einstein condensate interferometry as well as in quantum enhanced optical imaging and sensing techniques. Theoretical tools required for a comprehensive description of these systems must on one hand take into account atomic interaction leading to emergence of non-linear effects in system's dynamics, while on the other hand be able to describe in an efficient way the problem of simultaneous estimation of multiple-parameters. This last point closely relates to the earlier mentioned Heisenberg uncertainty relation, as in multi-parameter estimation problems the requirement to perform estimation of many parameters simultaneously prevents one in general from reaching the precision which might have been achieved if the measurement was focused on estimating the value of a single parameter only.

The project will also investigate connections between quantum metrology and quantum thermodynamics which deals with physics of microscopic quantum systems in contact with heat baths. As the end result of this research we expect to obtain new answers to the problem of simultaneous extraction of information and work from quantum systems, limits on power of quantum engines as well as minimal energy cost of performing metrological protocols.