PhD Thesis Defense MARIO NAPOLITANO 'Interaction-Based Nonlinear Quantum Metrology with a Cold Atomic Ensemble'

MARIO NAPOLITANO

February 07, 2014

Friday February 7, 11:00. ICFO Auditorium

MARIO NAPOLITANO

Quantum information with cold atoms and non-classical light

ICFO-The Institute of Photonic Sciences, SPAIN

In this manuscript we present an experimental and theoretical investigation of quantum-noise-limited measurement by nonlinear interferometry, or from another perspective, quantum-noise-limited interaction-based measurement. The experimental work is performed using a polarization-based quantum interface between propagating light pulses and cold rubidium-87 atoms trapped in an optical dipole trap.

We first review the theory of quantum metrology and estimation theory, and we describe theoretical proposals for nonlinear quantum metrology as developed by the group of Carlton M. Caves in the University of New Mexico.

We then describe our proposal, postulated in 2010, to implement the Caves group's ideas using nonlinear optical interactions in a cold atomic ensemble to implement a nonlinear spin measurement. To evaluate this proposal we develop two theoretical approaches, first an extension of the collective quantum variables approach, often employed to describe quantum interfaces and atomic spin ensembles, to nonlinear optical processes. This results in an effective Hamiltonian containing nonlinear terms of the form described by the Caves group, and demonstrates a qualitative equivalence of the two schemes. The second approach uses the Maxwell-Bloch equations to describe nonlinear propagation of pulses through an atomic spin ensemble, including inhomogeneities and relaxation effects. This latter method makes quantitative predictions about optical rotation signals under realistic experimental conditions.

We then describe the implementation of the proposal in a polarization-based light-atom quantum interface. We describe the existing trapping and probing system, focusing on the characteristics that make it suitable for shot-noise-limited and projection-noise-limited atomic spin measurements. We then describe adaptations to use the apparatus with shorter, higher-intensity pulses as required for nonlinear measurements, as well as characterization of the photodetection system under these modified conditions. Calibration of the nonlinear polarization rotation versus probe laser detuning allows us to produce a nearly pure nonlinear rotation signal.

Finally, experimental results are presented showing shot-noise-limited nonlinear rotation signals over three orders of magnitude in photon number N. The results are consistent with our theoretical models and confirm a major prediction of the Caves group's work, in that a two-photon interaction gives a scaling for the measurement sensitivity as N^{-3/2}.

A brief discussion relates this experimental observation to theoretical discussions of the "Heiseinberg limit" of quantum metrology, and possible further applications of nonlinear measurement techniques.

Friday February 7, 11:00. ICFO Auditorium

Thesis Advisor: Prof. Morgan Mitchell