PhD THESIS DEFENSE: Novel quantum interactions between light and dense atomic media

STEFANO GRAVA

October 28, 2022
10:00
ICFO Auditorium and Online (Teams)

The interface between light and cold atomic ensembles is a fundamental platform to unravel the quantum world and develop quantum technological applications. Its success relies on the simple idea that the efficiency of such an interface can be collectively enhanced by the use of many atoms. While the interaction between its building blocks, a single photon, and a single atom, is theoretically and experimentally understood, instead, the interaction between light and a macroscopic ensemble of motionless atoms is generically a complex system featuring multiple scattering and many-body dipole interactions. To avoid the complexity, typical theories of atom-light interactions treat the atomic medium as smooth. However, it is well-known that microscopic optical effects driven by atomic granularity can lead to important effects, especially in dense media. These phenomena and their consequences on

the performance of applications are not completely understood. To take them into account exactly, Chapter 1 introduces a ``spin model'' for light-matter interaction. The rest of the thesis is then divided into three chapters, which push forward our understanding of the interaction of light with dense atomic media.

In Chapter 2 it is argued that because of the overwhelming collective macroscopic response an ensemble can exhibit (well captured by the standard theory), many microscopically-driven effects that have been predicted, have also been challenging to observe so far. An essential step is thus to suppress the macroscopic light propagation, so as to allow the microscopic correlations to build up and to be analyzed in a background-free fashion. To solve this issue, a technique to suppress the macroscopic optical dynamics in free space, which allows to precisely investigate many-body aspects of light-matter interaction, will be presented and demonstrated. In particular, we unravel and precisely characterize a microscopic, density-dependent dipolar dephasing effect that generally limits the lifetime of the optical spin-wave order in ensemble-based atom-light interfaces.

In Chapter 3 we will go beyond the short-time and dilute limits considered previously, to develop a comprehensive theory of dephasing dynamics for arbitrary times and atomic densities. In particular, our non-perturbative approach is based on the strong-disorder renormalization group (RG), in order to quantitatively predict the dominant role that near-field optical interactions between nearby neighbors have in driving the dephasing process. This theory also enables one to capture the key features of the many-atom dephasing dynamics in terms of an effective single-atom model. These results should shed light on the limits imposed by near-field interactions on quantum optical phenomena in dense atomic media, and illustrate the promise of strong disorder RG as a method of dealing with complex microscopic optical phenomena in such systems.

Chapter 4 tries to answer the question of why ordinary materials exhibit a refractive index of order unity and if the answer can come from an electro-dynamical argument. While textbook theories predict nonphysical values when extrapolated to densities of solids, here, we will evaluate the exact linear optical response of a three-dimensional lattice of two-level atoms, first from the band structure and then from a direct numerical simulation. Interestingly, when multiple scattering of light is exactly taken into account, as a result of perfect interference, it is found that an ideal unity-filled array of atoms can have a refractive index that grows with the density and is furthermore real. This implies that a saturation mechanism for the index should come from the quantum chemistry interactions that arise in real materials. Whether saturation could be circumvented, could lead to novel optical materials with transformative technological potential.

Thesis Director: Prof Dr. Darrick Chang
Hosted by: Prof. Dr. Darrick Chang