Objective

I will develop an experimental research program in atomic, molecular and optical physics that studies optical phenomena in a highly-anisotropic sample of cold atoms. I will apply my knowledge of nonlinear optics, and atom cooling and trapping, to investigate optical pattern-formation, and the dynamics of cold atoms in this unique geometry. One specific effort will work towards guiding cold atoms from an anisotropic trap into a hollow-core waveguide.

Introduction

Revolutionary scientific advances are often associated with the discovery of phenomena that follow novel scaling laws. One example is the recent observation of superradiantly enhanced Fock-state emission [1, 2]. In this work the efficiency of on-demand photon emission is found to be greatly enhanced through the collective action of an atomic ensemble. This and other recent work suggests that collective systems take advantage of new physics that can be readily applied to many current problems in quantum information science.

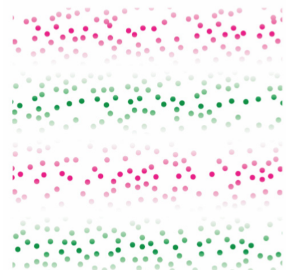

Figure 1: Atoms bunched and in phase, acting collectively [1]

Collective, or cooperative, phenomena arise in situations where the microscopic elements of a system interact in a synergistic way giving rise to phenomena that scale nonlinearly with the number of participants, i.e. the result is greater than the sum of the parts. As an example, N atoms superradiate when, in addition to the classical atomic dipoles being in phase, the position-dependent quantum phases of the N atomic states also constructively interfere (see Fig. 1). Through this interference the atoms couple to a common radiation field and radiate cooperatively with an intensity that scales as N^2.

In the field of atomic physics, collective phenomena have been proposed as elements in long distance quantum communication [3], and have been used in the experimental demonstration of on-demand Fock-state emission [2], quantum light-matter teleportation [4], and my own work on low light all-optical switching [5]. This general approach exploits the inherent complexity of collective quantum systems by replacing the complex apparatus used to interact with individual quantum systems with a simple apparatus used to interact with a collective system.

Several systems that lend themselves to collective quantum control have been developed recently. Rubidium vapor can be produced within the hollow core of a photonic crystal fiber (PCF) [7] which allows nonlinear optical interactions such as electromagnetically-induced transparency (EIT) to take place with very low amounts of optical power. Similar improvements have also been observed in highly anisotropic magneto-optical traps (MOTs). In these systems the phenomena that arise from coherent interactions between atoms and photons can also lead to recoil induced resonances as well as the collective cooling and self-organization of atoms [8, 9].

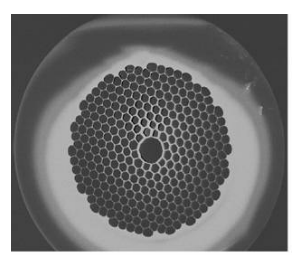

Figure 2: A hollow-core photonic crystal fiber [6]

In my graduate career, I have developed expertise in collective phenomena, nonlinear optics, and atom cooling and trapping. Through experimental, analytic, and numerical work, I have investigated the application of optical pattern formation to all-optical switching [5], where I demonstrated an all-optical switch that can be actuated with only a few thousand photons. The switch is based on nonlinear optical patterns which are one example of collective phenomena. I have also contributed to the design and construction of a highly-anisotropic 2D MOT [10], a system that will play a central role in the proposed research. As an example of applying atom cooling techniques to nonlinear optics research, I contributed to the first direct observation of optical precursors [11]. I have also worked with applications of nonlinear optics by merging nonlinear optics and fiber systems to develop broadband fiber-based slow-light systems [12].

My previous research projects have given me the skills necessary for successfully conducting a research program that will explore collective phenomena in novel experimental geometries with large optical depths. These phenomena are well suited to applications such as the coherent control of quantum systems. Additional goals of this program are to investigate nonlinear optics and atom dynamics in an optically thick sample of cold atoms.

A Two-dimensional Magneto-Optical Trap

To observe collective phenomena in an ensemble of atoms, the atoms must be relatively stationary and contained in a dense sample. To achieve these conditions, experimentalists typically rely on a magneto-optical trap (MOT). The MOT is a combination of magnetic and optical fields that can cool and trap atoms into a stable, dense cloud by inducing a position-dependent shift of the atomic resonance. This level-shift causes the probability of absorbing a photon of specific polarization to depend on the position of the atom. Since each photon absorption causes a change in atomic momentum, this combination of optical and magnetic fields gives rise to a spatially-restoring force. Additionally, doppler cooling can be induced by tuning the frequency of the trapping beams just below resonance. Doppler cooling creates "optical molasses" slowing the atoms as they enter the trapping region where they are then caught in the trapping potential. In the two decades since it was first demonstrated, the MOT has led to the broad sub-field of atom cooling and trapping. Moreover, the MOT has become a fixture in many research laboratories, opening the door to such revolutions as the observation of Bose-Einstein Condensation, and advancing the state of atomic clocks to an unprecedented level of accuracy.

My first project goal is the construction of a highly-anisotropic (2D) magneto-optical trap (MOT) similar to the design of Greenberg *et al*. [10]. This MOT offers an optical depth comparable to warm-vapor systems and with such a system, new work can be done to investigate recoil-induced resonances in the high gain regime [8], pattern forming optical instabilities [13], non-EIT based all-optical switching [8, 5], and atom interferometry [14], which require optical depths beyond those achievable in a traditional spherical MOT.

Cold Atoms in Hollow Optical Waveguides

To extend the application of a 2-D MOT, I will combine it with techniques for guiding cold atoms [15] and methods for coating the inner surfaces of PCF [7] in order to load laser-cooled atoms into a hollow-core fiber waveguide. The atom dynamics we have observed in an anisotropic cloud of trapped atoms suggest that the atoms can be readily guided along the long-axis of the trap. This is crucial to the ability to direct cold atoms into a hollow waveguide. Several techniques have been demonstrated for guiding atoms within optical fiber using beams of light de-tuned from an atomic resonance. Red-detuned beams, *i.e.* tuned below resonance, provide an attractive potential whereas blue-detuned beams (tuned above resonance) induce a repulsive potential. Thus red-detuned light coupled to the central mode of the fiber, or blue de-tuned light coupled as an evanescent wave will serve to guide atoms through the center of the hollow fiber core. The unique structures available in PCF allow even more possibilities that I will explore as part of this project. Atoms contained in this way would lead to an order of magnitude increase in the length of cold atom samples and provide a system ideally suited to the study of both collective atomic interactions and the associated self-organization observed in such systems.

As an initial application of a cold-atom fiber system, I will extend the work of Vuletić and coworkers [2] that demonstrated the use of a coherent ensemble of cold atoms in a moderate finesse cavity for single-photon emission. Instead of using a high finesse cavity, the direct increase in sample length offered by a cold-atom-filled fiber will allow the implementation of this scheme with a further increase in the efficiency of extracting single photons from the atomic system.

Other related applications for cold-atom-filled fiber would be as elements in the quantum information scheme proposed by Duan *et al*. [3] or in the related work on nonlinear optics with stationary light pulses [16]. The fundamental processes in these schemes scale as the optical depth of the sample so the fiber length allows for a large improvement over traditional vapor cells or spherical MOTs. Although progress has been made by Vengalattore *et al*. [8] with highly anisotropic MOTs, fiber-guided cold atoms will extend all of these results and many others based on collective effects including recoil-mediated and self-organization phenomena.

Educational and Institutional Benefits

The science behind cooling and trapping atoms is an elegant combination of many key concepts in physics: magnetic fields, lasers, geometrical optics, optical polarization, atomic energy level shifts, and photon momentum. The 2D MOT is a relatively complex system, however it also offers many potential research projects for undergraduates–even during the initial construction phase. Possible initial projects include: building a cavity-stabilized diode laser; stabilizing diode lasers with a dichroic atomic-vapor laser lock (DAVLL); designing, constructing and testing a vacuum system; and modeling and constructing a electromagnet system for the magnetic quadrupole fields used in the MOT.

A number of publications describe simplifications that can be made to the traditional spherical MOT design in order to make it suitable, and affordable, for undergraduate laboratory use. A 2D MOT can be built using many of the same components and thus for a comparable cost. The advantage is that many new experiments can be conducted in a 2D trap with a large optical depth that are not possible to conduct using a traditional spherical MOT.

This project utilizes a selection of standard optics equipment that students will learn to use: an optical table, oscilloscope, computer-controlled data acquisition system, acousto-optic modulators, laser diodes, power supplies, temperature controllers, vacuum systems, and atomic vapor cells. Students will also have the opportunity to develop skills for practical laser stabilization, atomic spectroscopy, and beam measurement techniques. During the course of undergraduate research in general, and this project in particular, students will acquire countless other practical skills ranging from basic electronics, to computer-instrument interfacing and automated data collection. I also emphasize the dissemination of research results via project web pages, poster and oral presentations, and peer reviewed journal articles.

In addition to my research experience, I bring the experience of working in collaboration with scientists in other departments and at other institutions, both at the formal level of subcontracted grants and on a more informal basis. Such collaborations can benefit research at small institutions by creating opportunities for highly competitive funding proposals where several investigators combine efforts and share resources.

The proposed project will provide a broad range of experimental experiences to undergraduate students. The research is of current interest to the AMO physics community and will enable a large number of further experiments in the fields of atom cooling and trapping and nonlinear optics. Students conducting this research will be well prepared for high-demand careers in the optics industry, or for graduate study, where there is also great demand.

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