Pattern Formation at Ultra-Low Light Levels
by Bonnie Schmittberger

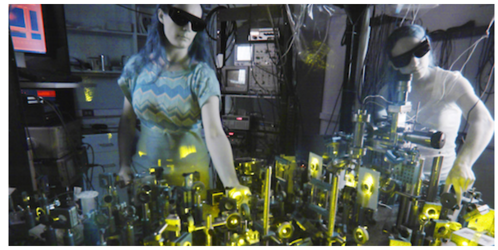
From swarming bacteria to social interactions among humans, the emergence of patterns in nature is ubiquitous. Pattern formation is often governed by collective dynamics, wherein individual components of a system begin to move or organize in a coherent way. The generation of patterns in nonlinear dynamical systems is found in nearly all subfields of science and provides insight into some of the most fundamental aspects of the world around us.

Nonlinear optical systems such as atomic ensembles exhibit pattern formation upon interaction with light. When the light-atom interaction is sufficiently strong, a sample of atoms will collectively scatter incident optical fields rather than absorbing and spontaneously re-emitting photons. Using certain optical field geometries, the collectively scattered optical fields form what are known as transverse optical patterns.

The ability to bias a system to exhibit one particular pattern is of great interest for dynamical systems in all branches of science [1]. In the field of optical pattern formation, the symmetry and type of the emitted pattern is selected by the initial conditions of the atomic ensemble [2]. A single fluctuation in the system may be all it takes to select a given pattern and define the macroscopic dynamics of the system. In order to choose a desired pattern, one must gain the ability to control the fluctuations that give rise to pattern formation.

The study of transverse optical pattern formation has provided great insights into pattern selection. At the Duke University Physics Department, the research group of Prof. Daniel Gauthier is devoted to understanding pattern formation in atoms. One of their goals is to improve existing techniques for pattern selection, which has applications not only in atomic and optical physics, but also in condensed matter physics and quantum information science. This research group demonstrated the ability to select a particular optical pattern by injecting a pulse of photons along a carefully chosen direction into a warm atomic vapor [3]. The ability to select a particular optical pattern also allowed them to create an all-optical switch that was controlled with only a few thousand photons.

Prof. Daniel Gauthier and his research group also demonstrated the first observation of transverse optical pattern formation in a sample of cold (slowly moving) atoms [4]. When the atomic sample consists of cold atoms, the atoms self-organize into spatial



structures defined by the interference pattern of the optical fields. These spatial atomic patterns and the transverse optical patterns are coupled and synergistically enhance one another. This complex interplay between the optical fields and the atoms also gives rise to enhanced material properties. As a result, they observe pattern formation at ultra-low light levels. This has important implications not only for improving techniques for pattern selection, but also for applications in low-light-level nonlinear optics.

This work is highly interdisciplinary and intersects with current research in quantum opto-mechanical systems where macroscopic objects are cooled to close to their quantum mechanical ground state and the general field of quantum information science where quantum bits are transformed from one domain (such as matter) to another (such as light), adds Prof. Gauthier.

With an enhanced material response, they may be able to create a single photon all-optical switch. If they achieve this goal, they will show that by applying the smallest possible perturbation, they can choose the complex large-scale behavior of a pattern-forming system.

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