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Light-induced self-organization in cold atomic clouds

Guillaume Labeyrie and Robin Kaiser

Abstract Patterns are ubiquitous in nature and have been extensively studied in biology, chemistry and physics including optics. We report here on experiments where pattern formation occurs in a cloud of laser cooled atoms. We identify three different mechanisms allowing spatial patterns to spontaneously emerge in either the atomic density, the excited state population, or the atomic spin state.

1 Experimental setup for self-organization in cold atoms

The typical setup used in these experiments is shown in [1](#). We prepare a cloud of cold ^{87}Rb atoms in a magneto-optical trap (MOT) using large diameter trapping laser beams. The produced cloud is cold ($\approx 100\ \mu\text{K}$), with a diameter larger than 1 cm, and contains up to 10^{11} atoms. The optical density for light resonant with the atomic transition is large, typically 100. The ability to produce such large clouds is an important prerequisite to realize these experiments. Once the cloud is prepared, we release it from the trap by shutting down both MOT beams and magnetic field gradient. Shortly after release, the cloud is illuminated by a linearly-polarized, pulsed "pump" laser beam (pulse duration 1 ms to 1 ms) of waist 2 mm, which is frequency

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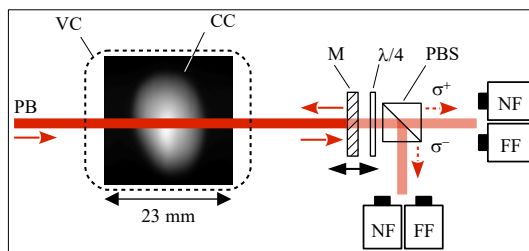


Fig. 1 Experimental setup for pattern observation. VC: vacuum chamber. CC: cold cloud. PB: pump beam. M: mirror. $\lambda/4$: quarter-wave plate. PBS: polarizing beam-splitter.

detuned from the atomic transition by δ (positive or negative). We use detunings larger than the atomic linewidth Γ (typically $|\delta/\Gamma| \approx 10$) such that most of the pump beam is transmitted by the cloud. This transmitted beam is then retro-reflected by a mirror located at a distance d behind the cloud.

The cloud behaves as an optical medium with a nonlinear index of refraction. If a small fluctuation of this index occurs in the plane transverse to the beam propagation axis, a small phase fluctuation is imprinted on the transmitted beam. After propagation in free space over $2d$, this phase fluctuation turns into an intensity fluctuation due to diffraction. This intensity fluctuation reacts on the nonlinear index of the cloud (optical feedback), and leads to a spontaneous oscillation in the transverse plane above a certain intensity threshold. Thus, one observes the appearance of a spatially modulated light intensity distribution in the transverse plane, with an underlying spatially modulated atomic susceptibility. We observe these light patterns by imaging the beam's transverse cross-section at a distance $2d$ after the cloud, using the small amount of light transmitted by the mirror as shown in 1. The field distributions can be recorded simultaneously in near-field (NF) and far-field (FF).

2 Different mechanisms for self-organization

In the course of this work, we observed different modes of self-organization depending on the experimental parameters. We demonstrated the existence of three distinct nonlinear mechanisms relying on different atomic degrees of freedom. In the following, we briefly describe these various mechanisms and the associated patterns.

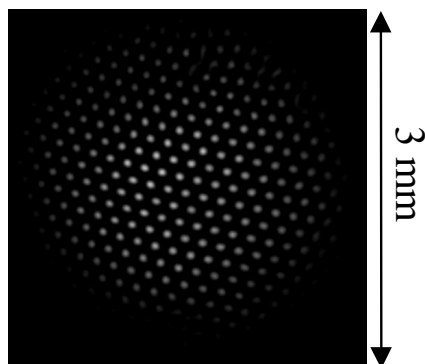


Fig. 2 Example of optomechanical patterns.

2.1 Optomechanical self-organization

This type of self-organization is observed for positive detunings, relatively low pump intensities (50 mW/cm^2) and pump pulse durations larger than $100 \mu\text{s}$. It relies on the dipole force exerted by the spatially modulated light on the cold atoms. Given sufficient time, the atoms spatially bunch into the potential wells, yielding a modulated index of refraction. Because the efficiency of this bunching process depends on the kinetic energy of the atoms, the intensity threshold for pattern formation depends of the temperature of the cloud in this situation. We show in 2 an example of self-organization in this case, where a nice hexagonal long range order is observed [1].

2.2 "Electronic" self-organization

To observe this type of self-organization we employ positive detunings as well, but higher pump beam intensities (above 200 mW/cm^2) and much shorter probe pulses ($\approx 1 \mu\text{s}$). In such a short time, the cold atoms cannot move over significant distances. Instead, the nonlinearity relies here on the saturation of the (quasi-2 level) atomic transition, which occurs when a significant amount of the population is transferred to the excited state. This is quantified by the so-called saturation parameter $s = (I/I_{sat})/[1 + 4 \cdot (\delta/\Gamma)]^2$. In this expression I is the pump laser intensity and I_{sat} an atomic parameter (here $I_{sat} = 3.6 \text{ mW/cm}^2$). For $s \ll 1$ the index of refraction is linear, for $s \approx 1$ the index is Kerr-like and for $s \gg 1$ the index saturates to 1. The observations reported in 3 are in agreement with this behavior. At low pump intensity (be-

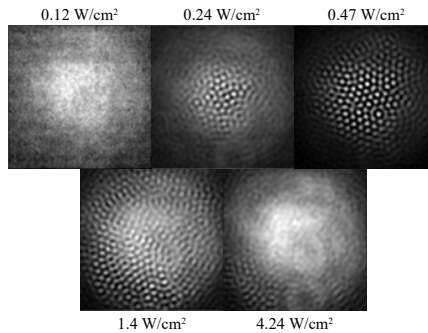


Fig. 3 Behavior of electronic patterns versus pump intensity.

low threshold) nothing occurs, then upon increasing I patterns appear and develop, and disappear again at high intensities due to the saturation of the index of refraction [2].

2.3 *Spin self-organization*

This regime of self-organization is drastically different from the two previous ones. It requires a negative detuning, and an accurate cancellation of residual magnetic fields. Once this is achieved, we apply a weak (≈ 1 G) magnetic field \mathbf{B} of controlled magnitude and direction, and observe the complex phase space shown in 4.

For $B \approx 0$, we observe structures with a square symmetry. The comparison of the images in the two circular polarization channels show that this is an anti-ferromagnetic state (AFM), with alternating domains with spin-up and spin-down atoms with equal populations [3, 4]. Increasing the longitudinal magnetic field B_z breaks the symmetry between s^+ and s^- and results in a ferro-magnetic phase (FM) of hexagonal symmetry, where one spin orientation dominates. A further increase of B_z results in a different phase (“high- B_z phase”), without long range order but with local hexagonal symmetry.

We also observe strikingly different behaviors versus transverse magnetic field. When the transverse magnetic field B_y (orthogonal to the input polarization) is increased, all patterns vanish. To the contrary, when B_x (parallel to the input polarization) is increased, a new phase (“coherence phase”) arises, without long-range order and with a peculiar symmetry. Both experimental observations and numerical simulations indicate that this phase is linked

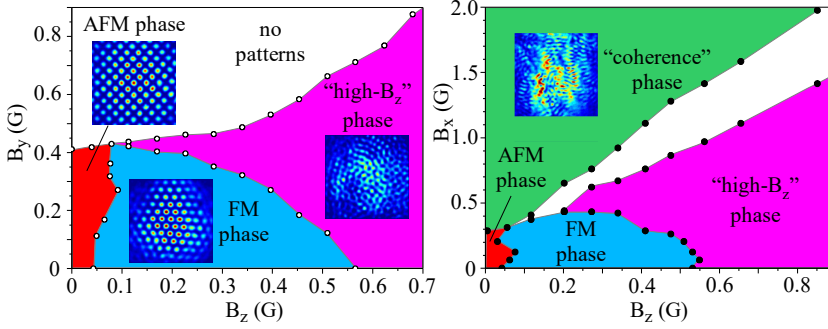


Fig. 4 Magnetic phase-space of spin patterns. B_x is the transverse component of the magnetic field parallel to the input polarization, B_y the transverse component of the magnetic field orthogonal to the input polarization, and B_z the component of the magnetic field along the pump beam propagation.

to the presence of a spatially-modulated coherence between ground states induced by the s^+/s^- fields [4].

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