Observation of spatial patterns and accurate atom number estimations in spinor Bose-Einstein condensates

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Application Note

Introduction

In our experiments at the Institute of Quantum Optics at the Leibniz Universität Hannover, we are investigating the behaviour of atoms at ultralow temperatures. We cool them from room temperature at about 300K below 1 µK, close to the absolute zero. At these low temperatures, the quantum nature of the atoms becomes important. They are losing their individuality and a so-called Bose-Einstein condensate (BEC) emerges where the atoms behave like a single macroscopic matter wave.

Experiment

We trap these BECs in a dipole trap. It consists of two crossed laser beams which form an attractive potential for the atoms in the crossing section. One advantage of such a trap is that the potential is independent of the internal spin state of the atoms. The atoms can be described as little magnets and the internal spin state then represents the orientation of these magnets. A simultaneous trapping of all spin states allows for the investigation of the dynamics of the atomic spins.

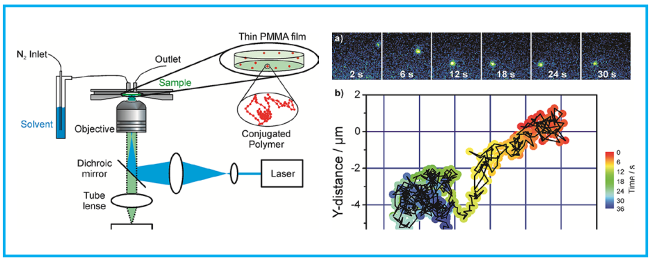

Figure 1: Simple model of the spinor dynamics. Left: dependence of the Zeeman-energy versus the magnetic field. Starting with an atom pair in the mF=0 substate, a collision leads to a transfer to the mF=±1 states. The energy ΔE0;1 is needed to lift one atom up to the mF=+1 state. The system gains (Δ E0;-1) from the drop of the second atom to the mF=-1 state. If now the difference of the two energies matches the energies of the effective trapping potential, the procecss is favorable and higher trapping modes are occupied (right).

In the experiments, the trapped, ultracold cloud of atoms is prepared such that the magnetization of all individual atoms is zero. As time goes by, pairs of atoms with zero magnetization may flip and produce a pair with magnetizations oriented up and down (Figure 1) [1]. At the same time, they change their external trapping state and occupy a higher trap level of the effective trapping potential. This leads to observable spatial distributions like in Figure 2 which can be described by Bessel functions [2]. These resulting clouds with the flipped spins have interesting properties. There is for example the amplification of vacuum-fluctuations [3], spontaneous symmetry breaking [2] or the preparation of non-classical states which beat the classical shot-noise limit.

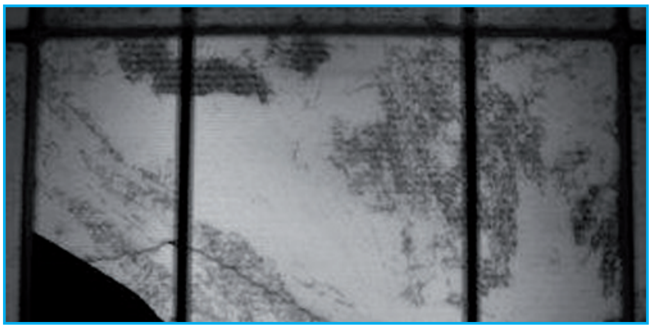

Figure 2: Picture of the atomic clouds in mF=±1 [2].The pictures are averages over several shots with the same experimental parameters. From left to right the applied magnetic field changes and so different trapping modes are populated. In the lower row there are theoretical simulations of the Bessel-functions which fit quite well to the observe structures.

For the analysis of these effects we need a versatile detection system with both high resolution to observe spatial pattern and low noise to precisely estimate the atom numbers. For the images, the atoms are released by switching off the trapping beams. During the following time of flight, an inhomogeneous magnetic field is applied to split up the different spin states of the atomic cloud. Then the resulting clouds are illuminated with a resonant laser beam and the shadow is mapped via one lens on the chip of the iXon+ EMCCD camera DV885 KCS-VP (Andor Technology). To remove perturbing effects caused by the laser beam and to calculate all relevant parameters of the cloud, we take a second picture without atoms 3 ms after the first one. We use the fast kinetics frame transfer mode of the camera for this procedure. It allows for taking two pictures right after each other where the time is only limited by the fast vertical shift speed of the pixels. For the analysis, we benefit from the low noise of the Peltier cooled EMCCD chip in the conventional amplifier mode and so we are able to precisely estimate the number of atoms from the two pictures. The uncertainty is about 40 atoms at a total number of several 104 atoms, a value smaller than the classical shot noise limit (at 100 atoms).
In the future, one can think about using the built in EM-gain and perform fluoresence detection to detect single pairs of entangled atoms.

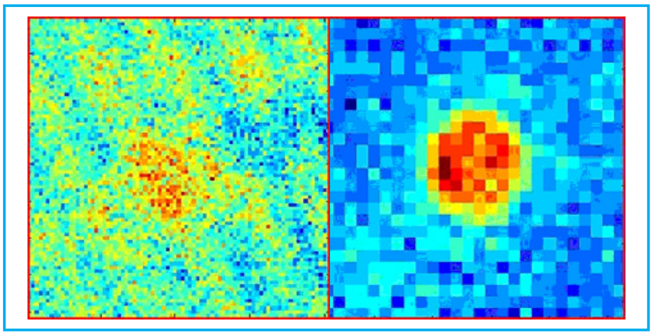

Figure 3: Comparison of the old (left) and the new (right) detection setup. Both false color picures are taken with the same number of atoms of about 1500. For the new detection scheme, we employed the DV885 and changed several optical elements which disturbed the iluminating laser beam

References

[1] **C. Klempt, O. Topic, G. Gebreyesus, M. Scherer, T. Henninger, P. Hyllus, W. Ertmer, L. Santos, and J. Arlt (2009)**: Multi-resonant spinor dynamics in a Bose-Einstein condensate, Phys. Rev. Lett. **103**, 195302 (2009)

[2] **M. Scherer, B. Lücke, G. Gebreyesus, O. Topic, F. Deuretzbacher, W. Ertmer, L. Santos, J. J. Arlt and C. Klempt (2010)**: Spontaneous breaking of spatial and spin symmetry in spinor condensates , Phys. Rev. Lett. **105**, 135302 (2010)

[3] **C. Klempt, O. Topic, G. Gebreyesus, M. Scherer, T. Henninger, P. Hyllus, W. Ertmer, L. Santos, and J. Arlt (2010)**: Parametric amplification of vacuum fluctuations in a spinor condensate, Phys. Rev. Lett. **104**, 195303 (2010)

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