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Production of spinor condensates of ^{87}Rb released from a magnetic trap

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Most of spinor condensates studied so far were produced *in situ* in dipole optical traps. Our new method allows production of spinor condensates in an expanding atomic cloud. Since the spinor condensate is created outside the trap, the Bose–Einstein condensate can be prepared in any trap, either magnetic or optical dipole, which significantly extends the experimental flexibility. The described method permits also study of collisions between low density spinor condensates.

Keywords: spinor condensates, Bose–Einstein condensate.

1. Introduction

Prepared in a highly controlled manner, ultra-cold atomic systems offer unique opportunities to study quantum dynamics and many-body quantum phases. As cooling techniques have advanced, atomic physicists have been able to make Bose–Einstein condensates (BECs) in dilute gases of alkali atoms [1–3]. Even though alkali atoms have angular momentum, the spin orientation is not a degree of freedom in magnetic traps. On the other hand, optical traps confine atoms independently of their spin orientation. This opens the possibility to study spinor condensates which represent a system with a vector, rather than a scalar, order parameter [4–6]. Spinor BECs, in which atoms may explore all sublevels of the hyperfine angular momentum F, hereinforth called spin, give access to interesting static and dynamical properties of a magnetic superfluid, such as spinor dynamics, spin domains, metastability, quantum tunneling and vortex dynamics [7–11].

Most of spinor condensates studied so far, were produced *in situ* in dipole optical traps. In the magnetic traps, atomic spin flips lead to untrapped states, which makes such traps useless for the study of the spinor condensates. A tight optical trap generally means that interactions of ultracold atoms are approximated by a contact potential. Indeed in alkali atoms, such as ^{23}Na and ^{87}Rb, the contact interactions play a dominant role in most of the experiments. The dipole interactions were so far experimentally studied only in the ^{52}Cr condensate [12] thanks to its magnetic dipole moment much larger than in alkali atoms.

In contrast to the *in situ* production, our method allows creation of spinor condensates in an expanding atomic cloud. The method is based on the appropriate sequence of magnetic perturbations and allows preparation of BEC in either magnetic or optical dipole trap.

2. Experimental setup

Our experimental setup contains a magnetic trap with the cigar-shaped harmonic potential with the axial frequency of $2\pi\times 12.1$ Hz and the radial frequencies tunable in the range of $2\pi\times 137$ to $2\pi\times 230$ Hz. We create BEC of up to 750000 ^{87}Rb atoms in the $|F = 2, m_F = 2\rangle$ hfs component of their ground state. This sample is analyzed by absorption imaging with the probe beam resonant with the $|F = 2, m_F = 2\rangle$–$|F = 3, m_F = 3\rangle$ hfs component of the ^{87}Rb D2 line. More experimental details can be found in Ref. [13].

Three pairs of Helmholtz coils allow to compensate stray magnetic fields with a precision of 5 mG. In the experiment, these coils are also used to control the local value of a weak, homogeneous magnetic field B_d during gravitational free fall of the BEC released from the trap.

3. Creation of spinor condensates

After preparation of the BEC of ^{87}Rb atoms in the $|F = 2, m_F = 2\rangle$ hyperfine state in a magnetic trap (MT), the trapping field is adiabatically replaced (*i.e.*, much slower than Larmor frequency) by the homogeneous, weak magnetic field B_d in a given direction. Atoms start to fall freely under gravity and their spins follow the magnetic field direction. After a given time of the free fall expansion (1–20 ms), the MT field is nonadiabatically pulsed for duration of 1–2 ms. For a distance long enough (about 1 mm), exactly below the trap center, the MT field is almost constant in the two horizontal directions and has the gradient of 100 Gs/cm in the vertical direction. The strongly inhomogeneous MT field $B_{\mathrm{S-G}}$ exerts a Stern–Gerlach (S–G) force on the falling BEC and atomic spins are projected onto the direction of the strong gradient of the magnetic field. For the $F = 2$ hyperfine component this creates up to five spinor condensates in all m_F magnetic sublevels depending on the angle between the B_d field and the $B_{\mathrm{S-G}}$ gradient, *i.e.*, the angle between atomic spins and the $B_{\mathrm{S-G}}$

gradient. The B_d field can be tuned in the range of –5 G to 5 G, while the absolute field $B_{\mathrm{S-G}}$ in the direction of the gradient can be set in the range of 30–80 G.

The Stern–Gerlach force separates the m_F condensates. The condensate spin-state projection into different spinor components happens only during short time of the $B_{\mathrm{S-G}}$ field pulse and afterwards the condensates in different momentum states return to one single spin state.

Subsequently, after few milliseconds, the condensates are recorded by a standard absorption imaging. During imaging, a short pulse of a weak magnetic field is applied, which allows optical pumping by the imaging beam. Thanks to this pumping, the absorption imaging detects atoms independently of their magnetic states. The schematic diagram of the process and the timing of the experiment are presented in Fig. 1.

The process has a remarkable resemblance to the Bragg scattering of Bose–Einstein condensate [14] where one can observe a collision of two condensates in different momentum states. Nevertheless, there are differences: first, during the $B_{\mathrm{S-G}}$ pulse, the colliding condensates are in different m_F states, and second, the momentum states of the components can be easily tuned by the duration and gradient of the $B_{\mathrm{S-G}}$ pulse.

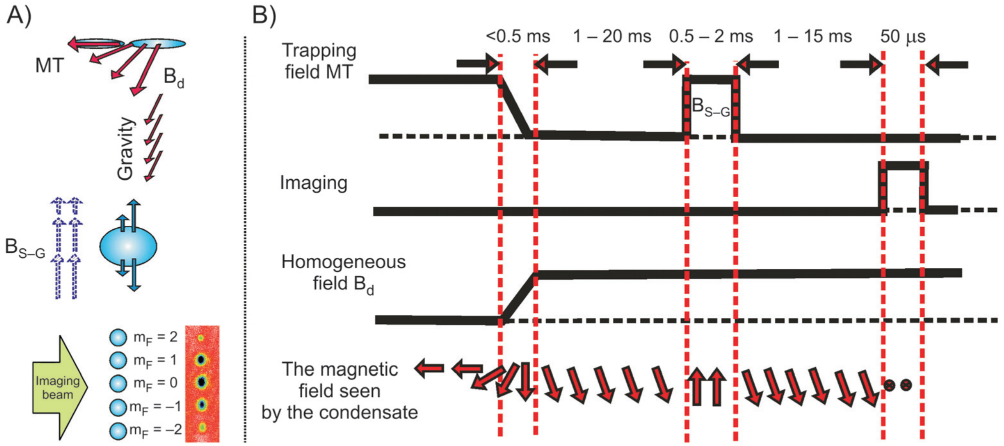

Fig. 1. A – Schematic diagram of the experiment. The field of the magnetic trap (MT) is adiabatically replaced by the homogeneous, weak magnetic field B_d in a given direction. Atoms start to fall freely under gravity and their spins follow the magnetic field direction. After a given time of free fall expansion (1–20 ms), the MT field is nonadiabatically pulsed for duration of 1–2 ms. Below the trap center, the MT field $B_{\mathrm{S-G}}$ is strongly inhomogeneous and exerts a Stern–Gerlach force on the falling BEC. The atomic spins are projected onto the direction of the strong gradient of the magnetic field. This creates up to five spinor condensates in all m_F sublevels of $F = 2$, with their populations depending on the angle between the B_d field and the $B_{\mathrm{S-G}}$ gradient. The S–G force separates the condensates and subsequently after few milliseconds the condensates are recorded by a standard absorption imaging. B – Timing of the experiment. In the bottom line, the direction of the magnetic field acting on the condensate is depicted by red arrows.

4. Results

Nonadiabatic switching of the quantization axis from the B_d direction to the $B_{\mathrm{S-G}}$ gradient projects atomic spins in all magnetic states with populations scaled as squares of the corresponding elements of the Wigner matrix. In the simplest case, when the magnetic field B_d is in the same direction as the local field in the center of the magnetic trap, the atoms do not change their spin orientation which during the fall remains the same as it was in the trap. The B_d field direction is then perpendicular to

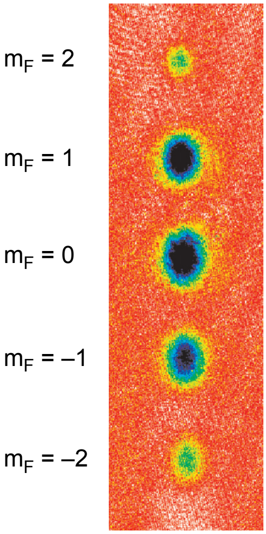

Fig. 2. Absorption image of the spinor condensates in the case of the B_d field perpendicular to the $B_{\mathrm{S-G}}$ gradient direction. The angle of 90° corresponds to the probabilities equal to 1/16, 1/4, 3/8, 1/4, 1/16 for $m_F = 2, 1, 0, -1, -2$, respectively.

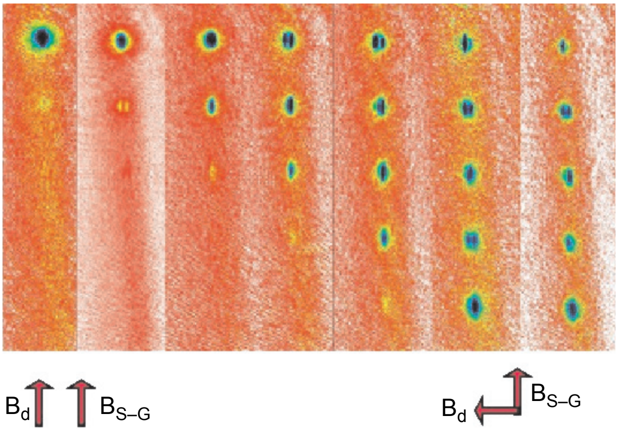

Fig. 3. Absorption images of the spinor condensates expanded by the Stern–Gerlach force for different orientations of the B_d versus the $B_{\mathrm{S-G}}$ field (false colors). If the direction of the B_d field is parallel to the $B_{\mathrm{S-G}}$ gradient (the leftmost image), only the $m_F = 2$ state is populated. Other directions of the B_d field result in mixed population distributions.

the $B_{\text{S-G}}$ gradient. The angle of 90° corresponds to the probabilities of the m_F sublevels 2, 1, 0, –1, –2 equal to 1/16, 1/4, 3/8, 1/4, 1/16, respectively.

Figure 2 shows the absorption image of the spinor condensates after the following timing sequence: 12 ms of the free fall in the B_d field of 1 Gs (the field of the same direction as the field in the center of the MT), perpendicular to the subsequent 2 ms $B_{\text{S-G}}$ gradient followed by 8 ms expansion, which allows the spinor condensates to separate. Measured relative populations of m_F equal 0.047 ± 0.018, 0.29 ± 0.02, 0.36 ± 0.02, 0.23 ± 0.02, 0.085 ± 0.019, which is close to the theoretical predictions.

Figure 3 shows a set of absorption images which were taken for different angles between the B_d field and the $B_{\text{S-G}}$ gradient. The timing of this experiment is the same as of the previous one. Tuning the direction of the B_d field allows one to control the populations of the spinor condensates created during the $B_{\text{S-G}}$ pulse. If the direction of the B_d field is parallel to the $B_{\text{S-G}}$ gradient, only the $m_F = 2$ or $m_F = -2$ states are populated. Other directions of the B_d field result in mixed population distributions.

There is an interesting internal structure in some of the individual momentum components. Its origin is yet to be explained and requires further study.

5. Conclusions

We presented the method which allows production of spinor condensates in an expanding atomic cloud. The BEC can be prepared in either magnetic or optical dipole trap. The method is based on an appropriate sequence of magnetic perturbations. Thanks to the reduction of the atomic density in an expanding BEC, the method allows studying of collisions between low density spinor condensates.

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References

[1] Anderson M.H., Ensher J.R., Matthews M.R., Wieman C.E., Cornell E.A., *Observation of Bose–Einstein condensation in a dilute atomic vapor*, Science **269**, 1995, pp. 198–201.

[2] Davis K.B., Mewes M.-O, Andrews M.R., van Druten N.J., Durfee D.S., Kurn D.M., Ketterle W., *Bose–Einstein condensation in a gas of sodium atoms*, Physical Review Letters **75**(22), 1995, pp. 3969–3973.

[3] Bradley C.C., Sackett C.A., Hulet R.G., *Bose–Einstein condensation of lithium: Observation of limited condensate number*, Physical Review Letters **78**(6), 1997, pp. 985–989.

[4] Myatt C.J., Burt E.A., Ghrist R.W., Cornell E.A., Wieman C.E., *Production of two overlapping Bose–Einstein condensates by sympathetic cooling*, Physical Review Letters **78**(4), 1997, pp. 586–589.

[5] Stamper-Kurn D.M., Andrews M.R., Chikkatur A.P., Inouye S., Miesner H.-J., Stenger J., Ketterle W., *Optical confinement of a Bose–Einstein condensate*, Physical Review Letters **80**(10), 1998, pp. 2027–2030.

[6] TIN-LUN HO, *Spinor Bose–Einstein condensates in optical traps*, Physical Review Letters **81**(4), 1998, pp. 742–745.

[7] SCHMALJOHANN H., ERHARD M., KRONJÄGER J., KOTTKE M., VAN STAA S., CACCIAPUOTI L., ARLT J.J., BONGS K., SENGSTOCK K., *Dynamics of F = 2 spinor Bose–Einstein condensates*, Physical Review Letters **92**(4), 2004, p. 040402; CHANG M.-S., HAMLEY C.D., BARRETT M.D., SAUER J.A., FORTIER K.M., ZHANG W., YOU L., CHAPMAN M.S., *Observation of spinor dynamics in optically trapped* ^{87}*Rb Bose–Einstein condensates*, Physical Review Letters **92**(14), 2004, p. 140403.

[8] STENGER J., INOUYE S., STAMPER-KURN D.M., MIESNER H.-J., CHIKKATUR A.P., KETTERLE W., *Spin domains in ground-state Bose–Einstein condensate*, Nature **396**, 1998, pp. 345–348.

[9] MIESNER H.-J., STAMPER-KURN D.M., STENGER J., INOUYE S., CHIKKATUR A.P., KETTERLE W., *Observation of metastable states in spinor Bose–Einstein condensates*, Physical Review Letters **82**(11), 1999, pp. 2228–2231.

[10] STAMPER-KURN D.S., MIESNER H.-J., CHIKKATUR A.P., INOUYE S., STENGER J., KETTERLE W., *Quantum tunneling across spin domains in a Bose–Einstein condensate*, Physical Review Letters **83**(4), 1999, pp. 661–665.

[11] SCHWEIKHARD V., CODDINGTON I., ENGELS P., TUNG S., CORNELL E.A., *Vortex-lattice dynamics in rotating spinor Bose–Einstein condensates*, Physical Review Letters **93**(21), 2004, p. 210403.

[12] STUHLER J., GRIESMAIER A., KOCH T., FATTORI M., PFAU T., GIOVANAZZI S., PEDRI P., SANTOS L., *Observation of dipole–dipole interaction in a degenerate quantum gas*, Physical Review Letters **95**(15), 2005, p. 150406.

[13] BYLICKI F., GAWLIK W., JASTRZĘBSKI W., NOGA A., SZCZEPKOWSKI J., WITKOWSKI M., ZACHOROWSKI J., ZAWADA M., *Studies of the hydrodynamic properties of Bose–Einstein condensate of* ^{87}*Rb atoms in a magnetic trap*, Acta Physica Polonica A **113**(2), 2008, p. 691.

[14] KOZUMA M., DENG L., HAGLEY E.W., WEN J., LUTWAK R., HELMERSON K., ROLSTON S.L., PHILLIPS W.D., *Coherent splitting of Bose–Einstein condensed atoms with optically induced Bragg diffraction*, Physical Review Letters **82**(5), 1999, pp. 871–875.

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