Kioloa, February 8, 2006

Chromium Bose-Einstein Condensates

Luis Santos

Universität Stuttgart

CO.CO.MAT

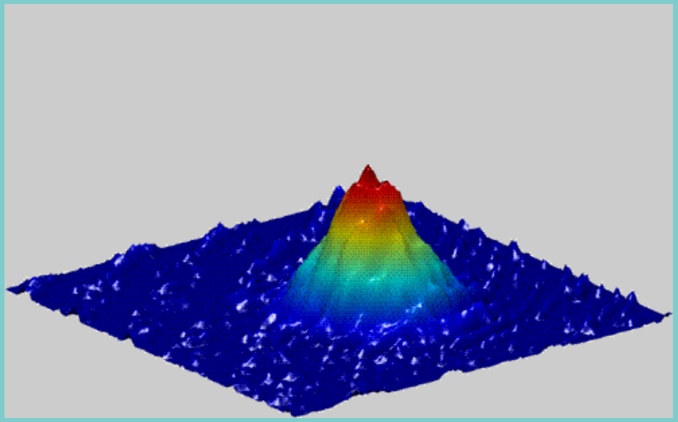
CONTROL OF QUANTUM CORRELATIONS IN TAILORED MATTER

SFB/TR 21 – STUTTGART, ULM, TÜBINGEN

Chromium BEC

BEC of Chromium atoms

[Griesmaier et al., PRL **94**, 160401 (2005)]



Also experiments on Chromium in Paris-Nord

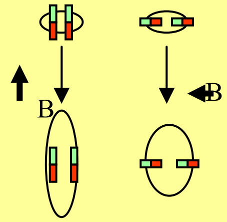
It is NOT just another BEC, because …

Chromium has a large magnetic moment, $\mu=6\mu_B$ → **First available dipolar BEC**

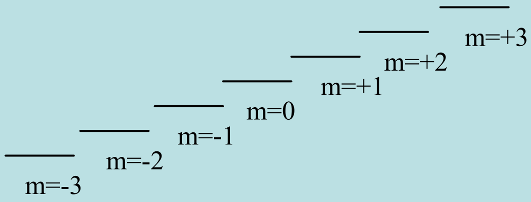
The ground state of ^{52}Cr is $^7S_3$ → **First available spin-3 BEC**

Outline of the talk

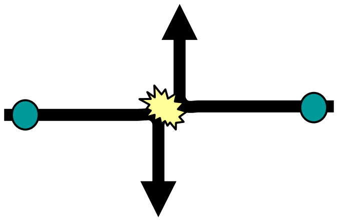
Dipolar gases



Cr-BEC as spin-3 BEC

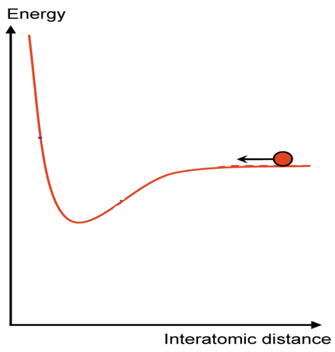


Dipolar gases



In typical experiments up to now the atoms interact via <u>short-range isotropic interactions</u>

The interaction is given by **<u>the s-wave scattering length “a”</u>**



$$V(\vec{r}-\vec{r}\,')\approx\frac{4\pi\hbar^2 a}{m}\delta(\vec{r}-\vec{r}\,')$$

Dipolar gases

Recent experimental developments open a novel research area in cold gases:

the analysis of dipolar gases

Atoms with large magnetic moment, as Cr [Griesmaier et al., PRL **94**, 160401 (2005)]

Polar molecules

Direct cooling of polar molecules [Bethlem and Meijer, Int. Rev. Phys. Chem. **22**, 73 (2003)]

Photoassociation of polar molecules in optical lattices [Jaksch et al., PRL **89**, 040402 (2002); Damski et al., PRL **90**, 110401 (2003); Rom et al., PRL **93**, 073200 (2004)]

Feshbach resonances in binary mixtures [Stan et al. PRL **93**, 143001 (2004); Inouye et al., PRL **93**, 183201 (2004); Petrov et al., cond-mat/0502010]

Laser induced dipole-dipole interaction [O'Dell et al., PRL **84**, 5687 (2000)]

Rydberg atoms [Jaksch et al., PRL **85**, 2208 (2000)]

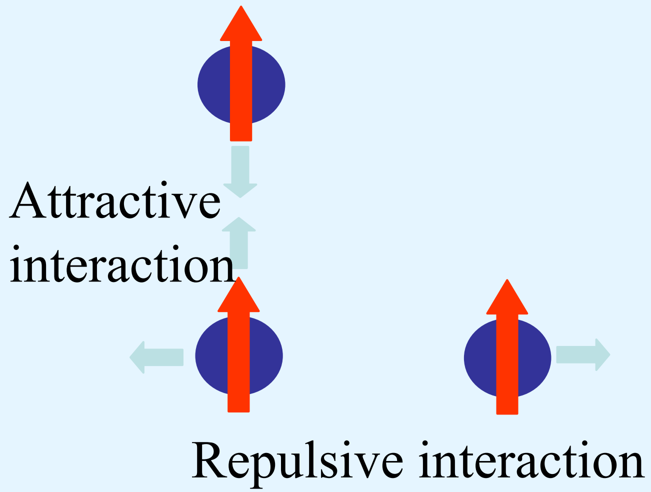
Dipolar gases

Dipole-dipole interaction

$$V(\vec{r}) = \frac{d^2}{r^3}\left(1 - 3\cos^2\theta\right)$$

The interaction is anisotropic (partially attractive and partially repulsive!)

Long-range interaction



Dipolar gases

At low temperatures the physics of a dipolar BEC is given by a nonlocal nonlinear Schrödinger equation

Nonlocal NLSE

$$i\hbar \frac{\partial}{\partial t}\psi(\vec{r},t) = \left\{ \begin{aligned} &\frac{-\hbar^2}{2m}\nabla^2 + V(\vec{r},t) + g\left|\psi(\vec{r},t)\right|^2 + \\ &+ g_d \int d\vec{r}\,' \frac{(1-3\cos^2\theta)}{\left|\vec{r}-\vec{r}\,'\right|^3}\left|\psi(\vec{r}\,',t)\right|^2 \end{aligned} \right\} \psi(\vec{r},t)$$

$g \propto a$ ⟷ $g_d \propto d^2$

Nonlocal nonlinearity is also observed in other physical systems

Plasma physics

[Litvak et al., Sov. J. Plasma Phys. **1**, 60 (1975)]

Nematic Liquid Crystals

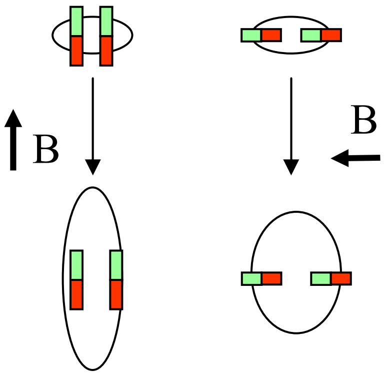
[Peccianti et al., Nature **432**, 733 (2004)]

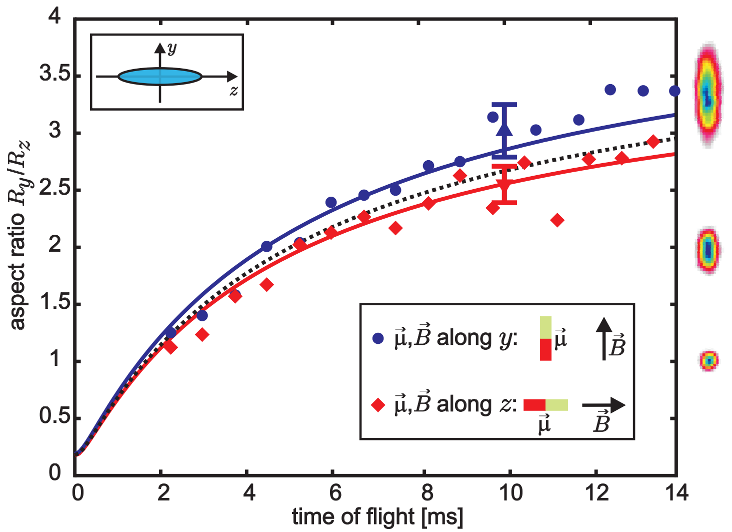
Dipolar gases

[Stuhler et al., PRL **95**, 150406 (2005)]

The expansion dynamics of a dipolar BEC is significantly affected by the dipolar interaction

[Góral and Santos, PRA **66**, 023613 (2002); Yi and You, PRA **67**, 045601 (2003); Giovanazzi *et al.*, J. Opt. B **5**, 208 (2003)]





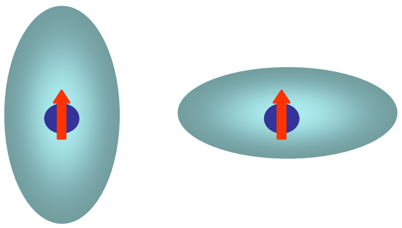
First trace of dipolar effects in BEC ever!!

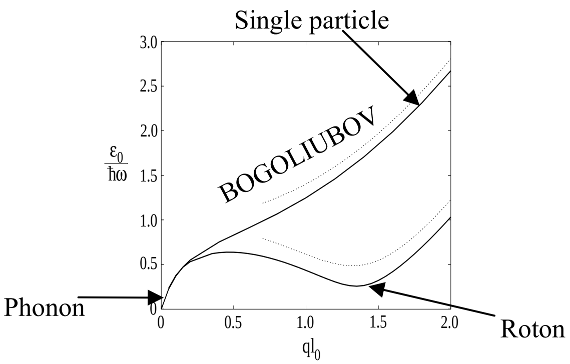
Dipolar gases

Dipolar BEC presents many novel characteristic features

Trap-dependent stability

[Yi and You, PRA **61**, 041604 (2000);
Góral et al., PRA **61**, 051601 (2000);
Santos et al., PRL **85**, 1791 (2000)]





Roton-maxon
excitation spectrum

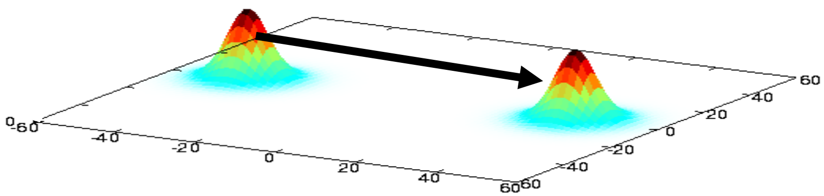
[O'Dell et al., PRL **90**, 110402 (2003);
Santos et al., PRL **90**, 250403 (2003)]

2D solitons

[Pedri and Santos,
PRL **95**, 150406 (2005)]

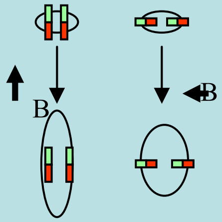
Inelastic scattering

Truly-2D motion without distortion!!

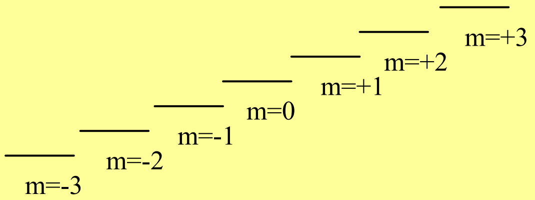


Outline of the talk

Dipolar gases



Cr-BEC as spin-3 BEC



Chromium BEC as a spinor BEC

Spin ½ $|F=1, m_F=-1\rangle$ $|F=2, m_F=+1\rangle$

Magnetically trapped ^{87}Rb

[Hall et al., PRL **81**, 1539 (1998)]

Spin 1 $|F=1, m_F=\pm 1,0\rangle$

Optically trapped

Na

[Stenger et al.., Nature 396, 345 (1998)]

^{87}Rb

[Schmalljohann et al., PRL **92**, 040402 (2004); Chang et al., PRL **93**, 170402 (2004); Higbie et al., PRL **95**, 050401 (2005)]

Spinor BEC

Spin 2 $|F=2, m_F=\pm 2,\pm 1,0\rangle$

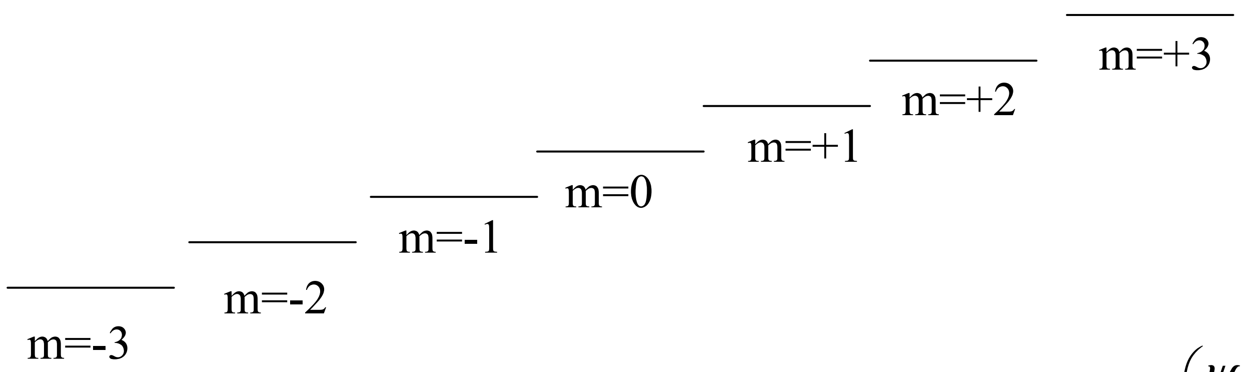
^{87}Rb

[Schmalljohann et al., PRL **92**, 040402 (2004); Kuwamoto et al., PRA **69**, 063604 (2004); Widera et al., PRL **95**, 190405 (2005)]

Chromium BEC as a spinor BEC

[Santos and Pfau, cond-mat/0510634]

The ground state of ^{52}Cr is $^{7}S_{3}$



$$\vec{\psi} = \begin{pmatrix} \psi_{-3} \\ \psi_{-2} \\ \psi_{-1} \\ \psi_{0} \\ \psi_{+1} \\ \psi_{+2} \\ \psi_{+3} \end{pmatrix}$$

Hence, unless we pump into one state (which is what is done up to now), we will have to deal with a **spinor wavefunction with 7 components !!!!**

Spin-3 BEC

Chromium BEC as a spinor BEC

Hamiltonian

$$\hat{H} = \hat{H}_0 + \hat{V}_{sr} + \hat{V}_{dd}$$

Single particle physics

Short-range interactions

Dipole-dipole interactions

$$\hat{H}_0 = \int d\vec{r} \sum_m \hat{\psi}_m^+(\vec{r}) \left[\frac{-\hbar^2}{2M} \nabla^2 + U_{trap}(\vec{r}) + pm \right] \hat{\psi}_m(\vec{r})$$

Zeeman effect $p = g\mu_B B$

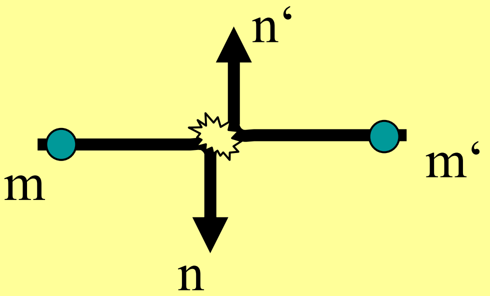
(No quadratic Zeeman effect in Cr-BEC)

Chromium BEC as a spinor BEC

Hamiltonian

$$\hat{H} = \hat{H}_0 + \hat{V}_{sr} + \hat{V}_{dd}$$

Single particle physics — Short-range interactions — Dipole-dipole interactions



$$\hat{V}_{sr} = \frac{1}{2}\int d\vec{r} \sum_S g_S \hat{P}_S(\vec{r})$$

[Ho, PRL 81, 742 (1998)]

They conserve the total spin : S=m+m‘=n+n‘

a_S s-wave scattering length for total spin S

Only even S is possible for Bosons: S=0,2,4,6

$$g_S = 4\pi\hbar^2 a_S / M$$

This is similar as for S=2, but having S=3 will lead to new physics!!

For ^{52}Cr:

[Werner et al., PRL **94**, 183201 (2005)]

$$a_0 = ? \qquad a_4 = 58(6)a_B$$

$$a_2 = -7(20)a_B \qquad a_6 = 112(14)a_B$$

Chromium BEC as a spinor BEC

Hamiltonian

$$\hat{H} = \hat{H}_0 + \hat{V}_{sr} + \hat{V}_{dd}$$

Single particle physics ($\hat{H}_0$)

Short-range interactions ($\hat{V}_{sr}$)

Dipole-dipole interactions ($\hat{V}_{dd}$)

They do **NOT** conserve the total spin

$$\hat{V}_{dd} = \frac{c_d}{2} \int d\vec{r} \int d\vec{r}\,' \frac{1}{\left|\vec{r} - \vec{r}\,'\right|^3} \hat{\psi}^+_m(\vec{r}) \hat{\psi}^+_{m'}(\vec{r}\,') \begin{bmatrix} S_{mn} \cdot S_{m'n'} - \\ 3(S_{mn} \cdot e)(S_{m'n'} \cdot e) \end{bmatrix} \hat{\psi}_n(\vec{r}) \hat{\psi}_{n'}(\vec{r}\,')$$

This violation of the spin conservation means that

spin can be transferred into center-of-mass angular momentum!!

$S = \left(S_x, S_y, S_z\right)$ are the spin-3 matrices

$e = \left(\vec{r} - \vec{r}\,'\right) / \left|\vec{r} - \vec{r}\,'\right|$

Chromium BEC as a spinor BEC: Ground state

Mean-field approximation $\hat{\psi}_m(\vec{r}) \cong \sqrt{N}\psi_m(\vec{r})$

Single-mode approximation $\psi_m(\vec{r}) = \Phi(\vec{r})\psi_m$

Magnetic field in z-direction

$$E[\{\psi_m\}] \cong \tilde{p}\langle S_z\rangle + \tilde{c}_1\langle S_z\rangle^2 + \frac{4}{7}c_2|\Theta|^2 + c_3\left(\frac{3}{2}\langle S_z^2\rangle^2 - 12\langle S_z^2\rangle + \frac{1}{2}\left|\langle S_+^2\rangle\right|^2 + 2\left|\langle S_+S_z\rangle\right|^2\right)$$

$$c_1 = (g_6 - g_2)/18 \approx 0.65 g_6$$

$$c_2 = g_0 + (-55g_2 + 27g_4 - 5g_6)/33 \approx g_0 + 0.374 g_6$$

$$c_3 = g_2/126 - g_4/77 + g_6/198 \approx -0.002 g_6$$

$$\Theta = \frac{1}{2}\sum_m (-1)^m \psi_m \psi_{-m}$$

$$\tilde{p} = 2p\Big/N\int d\vec{r}\left|\Phi(\vec{r})\right|^4$$

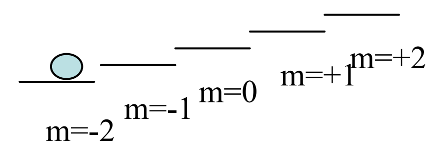
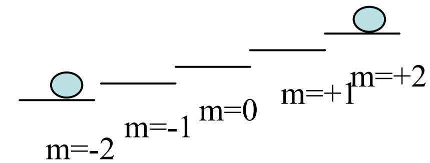
Chromium BEC as a spinor BEC: Ground state

In order to get a feeling, let's compare with spin-2 BEC

[Ciobanu et al., PRA 61, 033607 (2000); Koashi and Ueda, PRL 84, 1066 (2000)]

$$E \cong \tilde{p}\langle S_z\rangle + c_1 \langle S_z\rangle^2 + \frac{4}{5} c_2 |\Theta|^2$$

The same but without the c_3 term !!

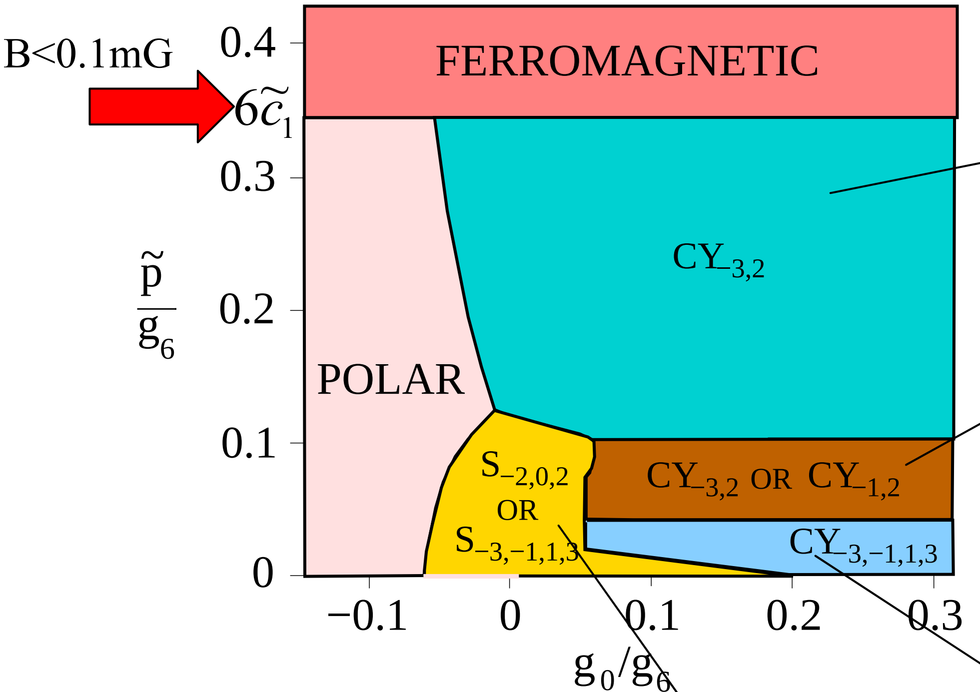
Ferromagnetic	$\Theta = 0$ $\lvert\langle S_z\rangle\rvert = 2$	$c_1 \leq \tilde{p}/4$ $c_1 - c_2/20 \leq \tilde{p}/4$	
Polar ^{87}Rb	$\Theta \neq 0$	$c_2 < 0$ $c_1 - c_2/20 > \tilde{p}/4$	
Cyclic	$\Theta = 0$ $\lvert\langle S_z\rangle\rvert \neq 2$	$c_2 > 0$ $c_1 > \tilde{p}/4$	Relative phases important

For spin-1: only ferromagnetic (^{87}Rb) or polar (Sodium) [Ho, PRL **81**, 742 (1998)]

Chromium BEC as a spinor BEC: Ground state

$$E[\{\psi_m\}] \cong \tilde{p}\langle S_z\rangle + \tilde{c}_1\langle S_z\rangle^2 + \frac{4}{7}c_2|\Theta|^2 + c_3\left(\frac{3}{2}\langle S_z^2\rangle^2 - 12\langle S_z^2\rangle + \frac{1}{2}\left|\langle S_+^2\rangle\right|^2 + 2\left|\langle S_+S_z\rangle\right|^2\right)$$

$$\langle S_+S_z\rangle = 0$$



$$\begin{cases} \langle S_z\rangle = -\tilde{p}/2\tilde{c}_1 \\ \Theta = 0 \quad \langle S_+^2\rangle = 0 \\ \langle S_z^2\rangle = 6 + \tilde{p}/2\tilde{c}_1 \end{cases}$$

$$\begin{cases} \langle S_z\rangle = -\tilde{p}/2\tilde{c}_1 \\ \Theta = 0 \quad \langle S_+^2\rangle = 0 \\ \langle S_z^2\rangle = 6 + \tilde{p}/2\tilde{c}_1 \quad \text{or} \quad 2 - \tilde{p}/2\tilde{c}_1 \end{cases}$$

$$\Theta = 0 \quad \langle S_+^2\rangle \neq 0$$

$$\Theta \neq 0 \quad \langle S_+^2\rangle \neq 0$$

Biaxial nematics

[Diener and Ho, cond-mat/0511751]

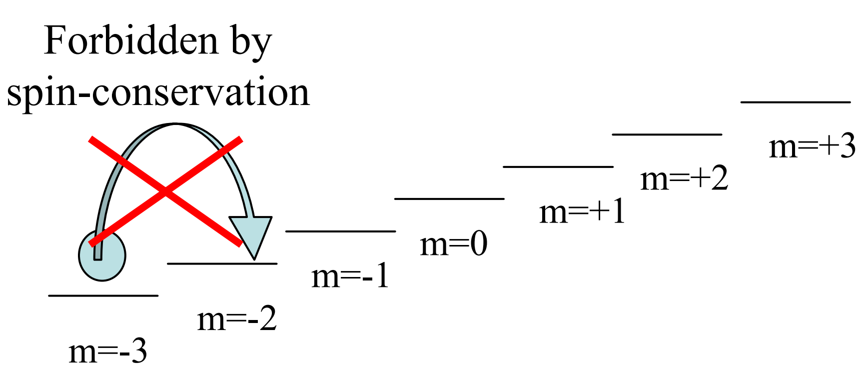
[Madsen et al., PRL **92**, 45505 (2004); Acharya et al., PRL **92**, 145506 (2004)]

Chromium BEC as a spinor BEC: Dynamics

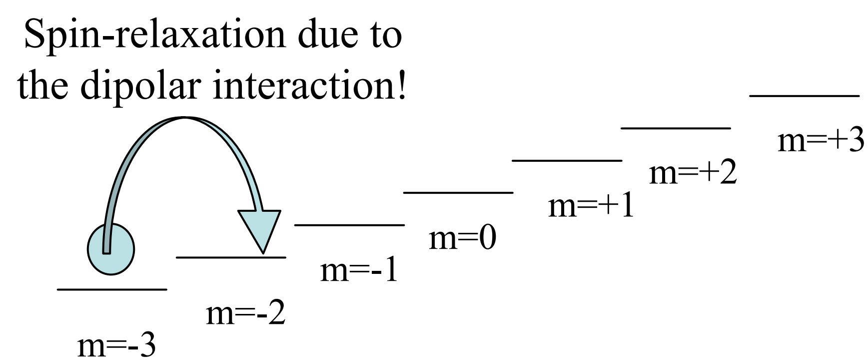
The dipole-dipole interaction plays a little role in the ground-state properties

But it can play a crucial role in the dynamics!

Only short-range part



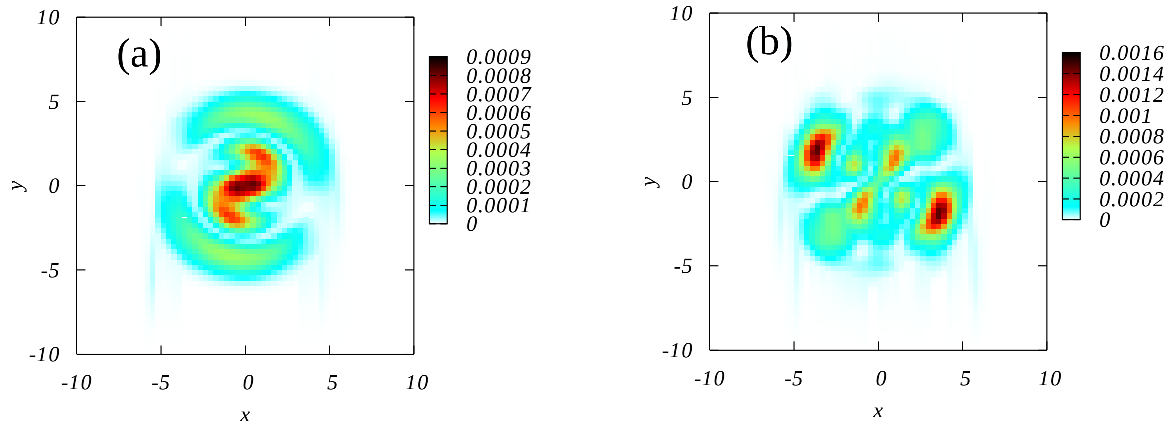
With dipolar interaction



The loss in spin, must be gained by the center of mass angular momentum

Chromium BEC as a spinor BEC: Dynamics

Density for the state m=-2



The state m=-2 starts to rotate!

It resembles the Einstein-de Haas effect

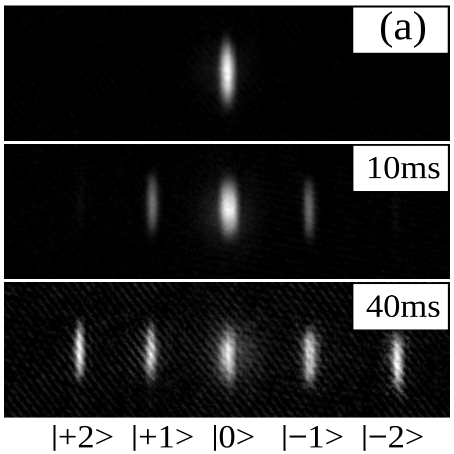
[Kawaguchi et al., cond-mat/0511052]

The coherent EH-effect is destroyed if $g\mu_B B >> \hbar\omega$

Chromium BEC as a spinor BEC: Dynamics

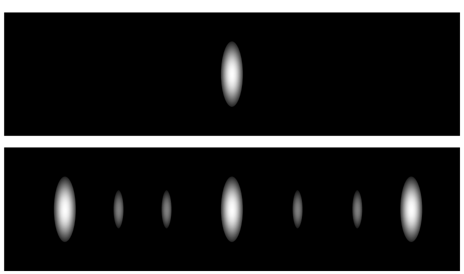
Also the c_3 terms have a significant role int he spinor dynamics and may lead to a rapid transfer from m=0 to m=+3 and m=-3

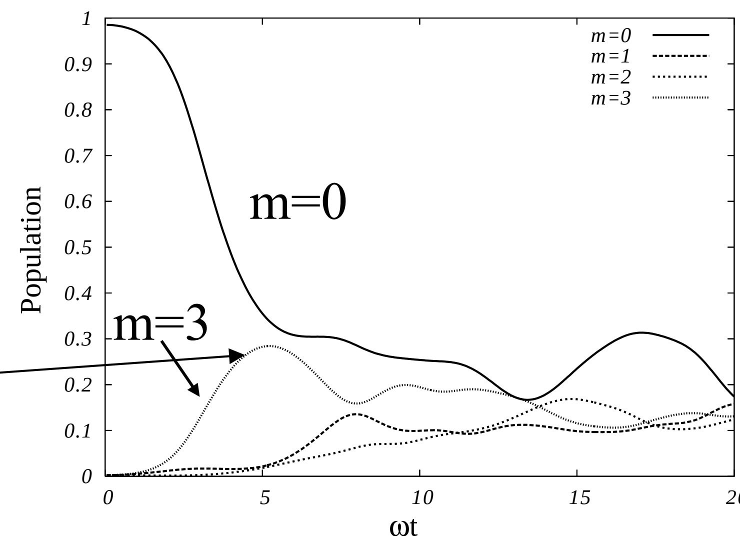
^{87}Rb



For F=2 a sequential population is observed

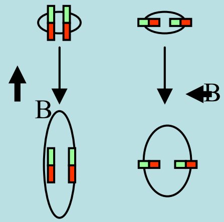
[Schmalljohann et al., PRL **92**, 040402 (2004)]



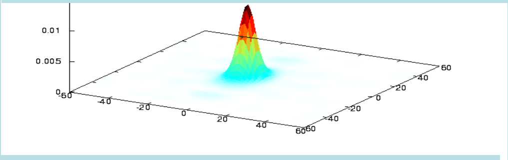


Summary

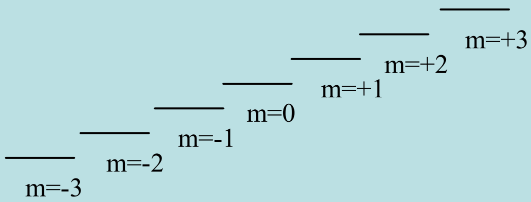
Properties of Dipolar BECs



Nonlocal nonlinearity. Multidimensional solitons



Cr-BEC as spinor BEC



1D Dipolar gases

[Sinha and Santos, in preparation)]

Dipolar Lattice gases

[Góral et al., PRL **88**, 170406 (2002)]

Fermionic dipolar gases [Baranov et al., PRL **92**, 250403 (2004)]

Rotating dipolar gases [Baranov et al., PRL **94**, 070404 (2005); Rezayi et al., cond-mat/0507064]

Quantum information [Brennen et al., PRL **82**, 1060 (1999); Jaksch et al., PRL **85**, 2208 (2000); DeMille et al., PRL **88**, 067901 (2002)]

People

Universität Stuttgart

P. Pedri	J. Stuhler
S. Sinha	A. Griesmaier
S. Giovanazzi	T. Koch
R. Nath	M. Fattori
L. Santos	T. Pfau

M. Baranov, B. Damski, K. Góral, M. Lewenstein,
E. Tiemann, G. V. Shlyapnikov, S. Kotochigova
P. Julienne, P. Zoller