Thermodynamics of Spin 3 ultra-cold atoms with free magnetization

B. Pasquiou, G. Bismut (former PhD students), B. Laburthe-Tolra, E. Maréchal, P. Pedri, **L. Vernac**, O. Gorceix
Université Paris 13, Laboratoire de Physique des Lasers, CNRS, UMR 7538, 93430 Villetaneuse France

Chromium atoms have a large magnetic moment of 6 Bohr magneton : dipole-dipole interactions (DDIs) are much larger than in alkaline atoms.
As a consequence, these strong DDIs offer the possibility to investigate the physics of **a BEC with free magnetization**.
When the external magnetic field is lowered to the mGauss range, we observe a spontaneous demagnetization of the BEC : all Zeeman substates become populated.

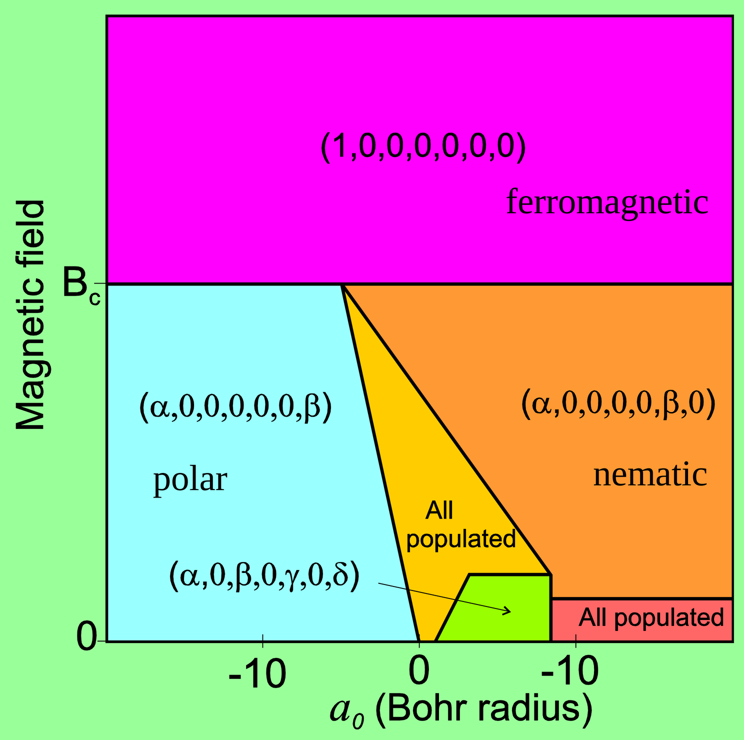
Our work is described in B. Pasquiou et al., Phys. Rev. Lett. 106 , 255303 (2011) and Phys. Rev. Lett. 108 , 045307 (2012)

Quantum phase diagram of the chromium BEC (S=3) at low magnetic field

Contact interactions dominate, atoms interact through 4 molecular potentials, corresponding to $S_{2\,body}$ = 6, 4, 2 and 0

Measured : $a_6 = 103\ a_{Bohr}$, $a_4 = 64\ a_{Bohr}$ deduced : $a_2 = -7\ a_{Bohr}$ unknown : a_0

As a_6 is not the smallest, **the ground state is not anymore ferromagnetic** at low B field



Value of the critical field B_c :

$$g\ \mu_B\ B_c = 0.7\frac{2\pi\ \hbar^2}{m}\left(a_6 - a_4\right)\ n$$

for $n = 3.10^{14}$ cm^{-3}, B_c = 0,25 mG

B_c is reachable even in a non magnetic shielded environment !

That is not the case with alkaline
Example : B_c = 10 μG for Rb (a_2-a_0 small)

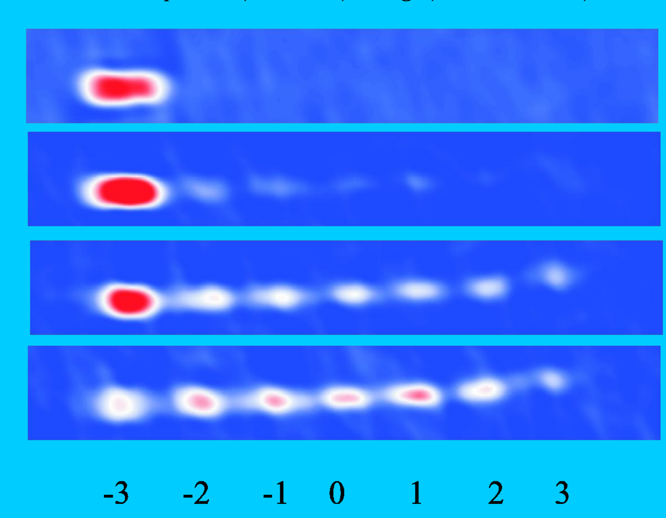
When lowering the magnetic field below B_c, **a quantum phase transition** is expected

Ref Diener et Ho, PRL **96**, 190405 ; Santos et Pfau, PRL **96**, 190404

Demagnetization of the BEC after a quench of the magnetic field

We suddenly reduce the value of the B field from 20 mGauss to a very low value.
The field decreases with a 1/e time of 8 ms, set by Eddy currents.

The BECspin composition at low field can be revealed by Stern-Gerlach analysis. The absorption pictures above have been taken after 150 ms of free evolution in the low B field, equal to a) 1 mG; b) .5 mg c) .25 mG and d) "0" mG.



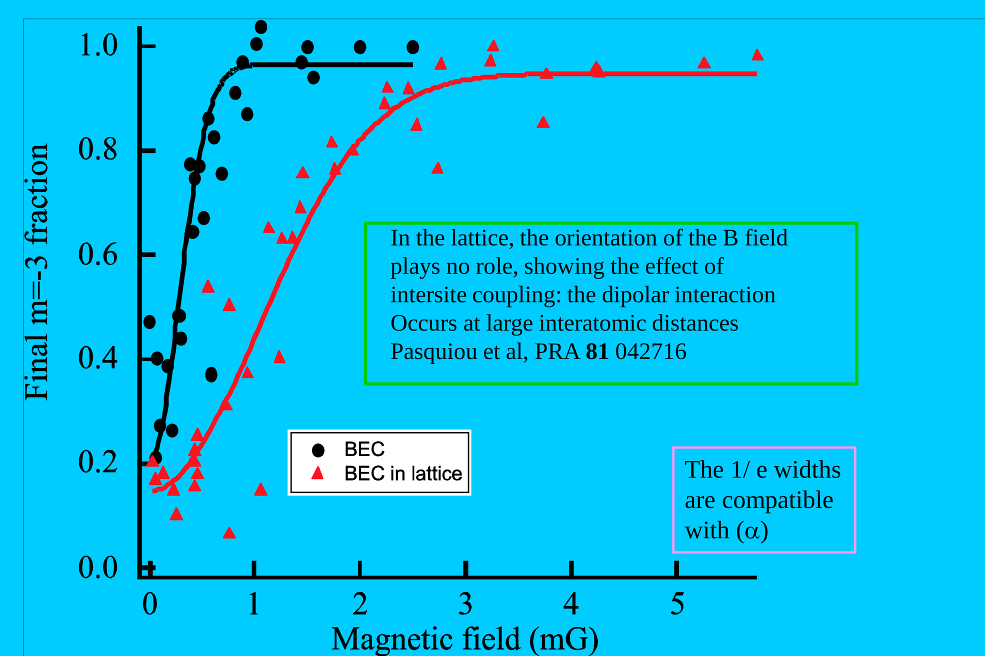
At "B =0", the spin populations are: {18+/-9, 18+/-4, 14+/-1.5, 15+/-3, 17+/-3, 12.5+/-4, 6+/-2}

Characteristics of the BEC:
N_{atoms} = 20000, μ = 4 kHz
peak density = 3.10^{14} cm^{-3}
trap frequencies = 300, 400 and 550 Hz

We can do the same experiment with the BEC loaded in **a 2D optical lattices**.

Characteristics of the 1D quantum gases:
- depth = 25 E_R = 120 kHz >> μ = 11 kHz
- peak density = 2.10^{15} cm^{-3}
- larger volume than the BEC (factor 3)

Depolarization as a function of the magnetic field



In the lattice, the orientation of the B field plays no role, showing the effect of intersite coupling: the dipolar interaction
Occurs at large interatomic distances
Pasquiou et al, PRA **81** 042716

The 1/ e widths are compatible with (α)

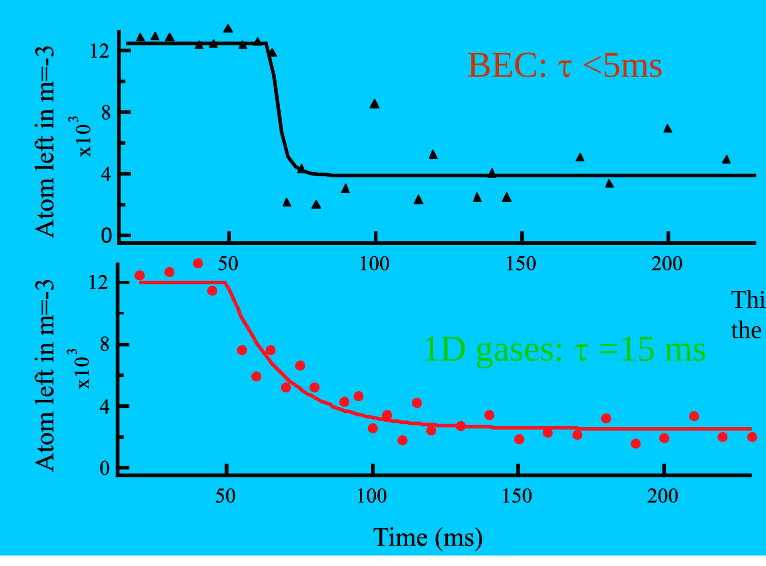
Experimental stabilization of the B field

A 3 axis fluxgate sensor located at 15 cm of the chamber measures the B field for control
An active compensation drive current in three pairs of large rectangular coils located at
1 m of the BEC ; the measurement of the residual B field fluctuations is made with an
other sensor located at 20 cm from the first one

Results:
AC noise = 500 μG, but is screened by the vacuum chamber
DC fluctuations = 100 μ G on a one hour time scale

Dynamics of the demagnetization

The evolution is faster in the BEC case !



For atoms loaded into an optical lattice, the large increase of the (repulsive) contact mean-field forces the cloud to swell.
The overall volume of the cloud is then increased by a factor of about three, hence reducing the dipolar mean-field.
A slower depolarization dynamics in the lattice is a consequence of the non local character of DDI, and indicates inter-site inelastic dipolar couplings in the lattice.

A simple model to account for the depolarization dynamics:

We calculate the dynamics for the population transfer in m_S=-2 at short time, assuming Γ_{-2} << 1.
The dynamics between the ϕ_{-3} and ϕ_{-2} components is then given by:

$$i\hbar\frac{d}{dt}\begin{pmatrix}\phi_{-3}\\ \phi_{-2}\end{pmatrix} = H_{tot}\begin{pmatrix}\phi_{-3}\\ \phi_{-2}\end{pmatrix}$$

$$H_{tot} = \begin{pmatrix}H(\vec r) & \hbar\,\Gamma\\ \hbar\,\Gamma & H(\vec r) + g\,\mu_B\end{pmatrix}$$

$$\gamma = 3S^{3/2}\hbar^2 d^2/\sqrt{2} \qquad d^2 = \mu_0 (g_J\,\mu_B)^2/4\pi$$

$$\Gamma(\vec r) = \gamma \int d^3r' \frac{\left((x-x') - i(y-y')\right)(z-z')}{|\vec r - \vec r'|^5} |\phi_{-3}(\vec r')|^2$$

This gives Γ^{-1} = 3 ms and 10 ms for resp. the BEC and the 1D quantum gases

Dynamics for B_{dd} < B < B_c is under study

$$B_{dd} = \frac{\hbar\ \Gamma}{g\ \mu_B} \approx 0.1\ mG$$

Thermodynamics properties above B_c

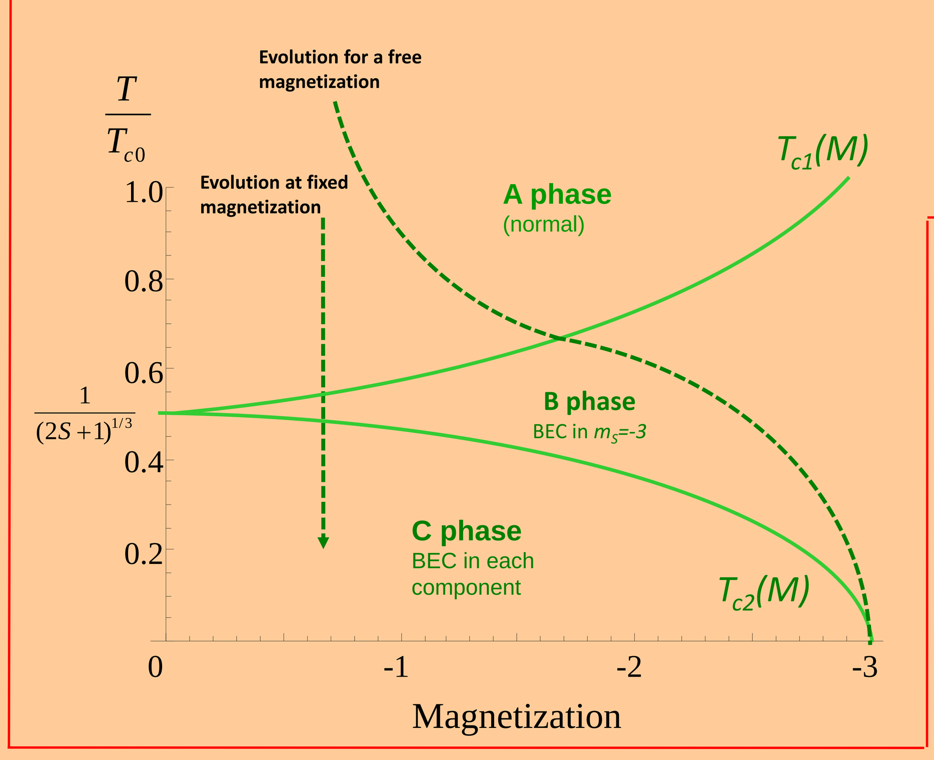
S=3 spinor gas: the non interacting picture

Single component Bose thermodynamics

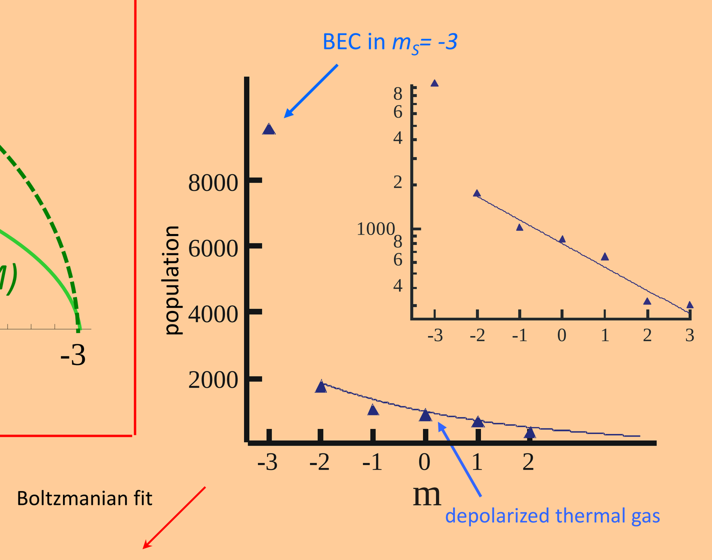
$$g_J \mu_B B >> k_B T \qquad k_B T_{c0} = 0.94\ \hbar\bar\omega N_{at}^{1/3}$$

Multi-component Bose thermodynamics

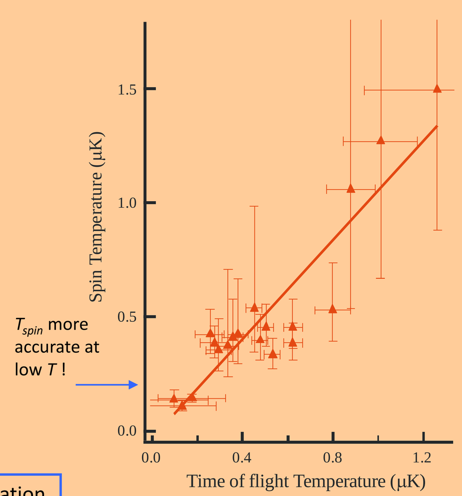
$$g_J \mu_B B \approx k_B T \qquad \mu_i = \mu + g_J \mu_B m_i B \qquad T_c \underset{B\to 0}{\to} \frac{1}{(2S+1)^{1/3}} T_{c0}$$



A « bi-modal » spin distribution



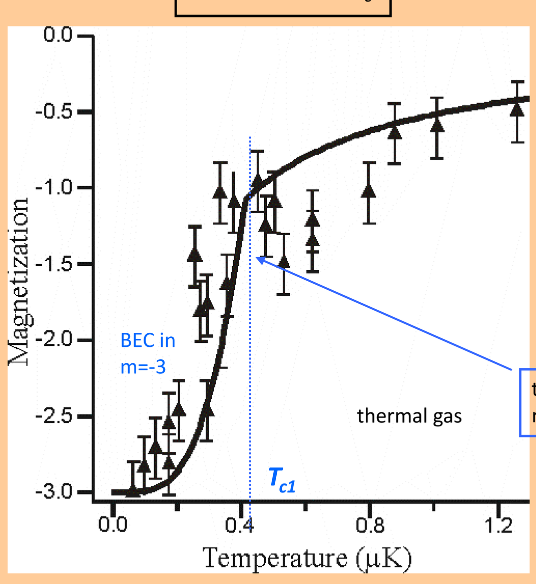
A new thermometry



Only thermal gas depolarizes
Cooling scheme if selective losses for m_s > -3
e.g. field gradient

Experimental Results

$B = 0.9\ mG > B_c$



the kink in magnetization reveals BEC

Solid line: results of theory without interactions and free magnetization

T_{c1} is the critical temperature for condensation of the spinor gas (in the m_s=-3 component)

The good agreement shows that the system behaves as if there were no interactions
(expected for S=1)

Isoshima et al., J. Phys. Soc. Jpn, 69, 12, 3864 (2000)

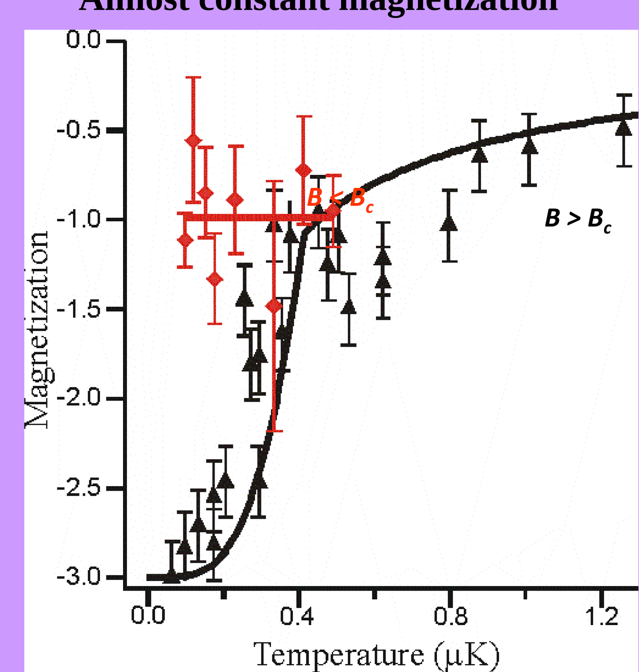
$$B \to 0 \swarrow \quad \frac{1}{(2S+1)^{1/3}} T_{c0} < T_{c1} < T_{c0} \quad \searrow B \to \infty$$

The BEC is ferromagnetic: only atoms in m_S=-3 condense

(i.e. in the absolute ground state of the system)

Thermodynamics properties below B_c

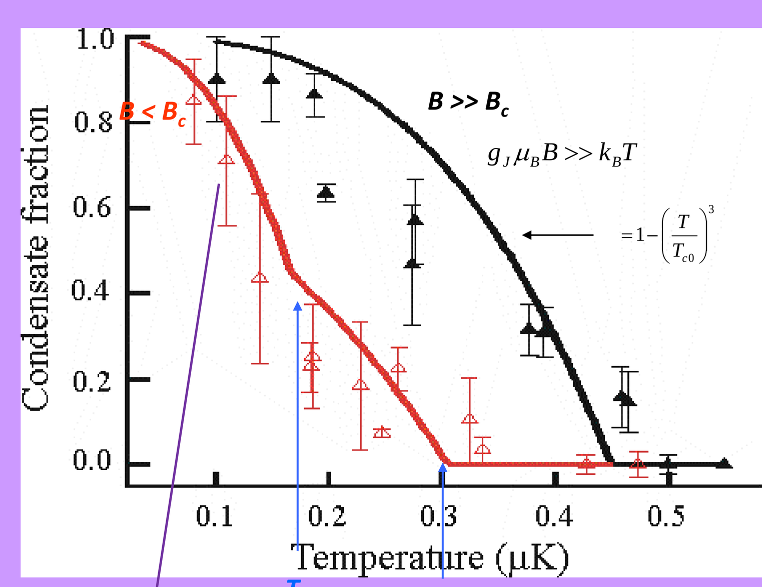
Almost constant magnetization



for B < B_c, magnetization remains constant after the demagnetization process independent of T

This reveals the non-ferromagnetic nature of the BEC below B_c

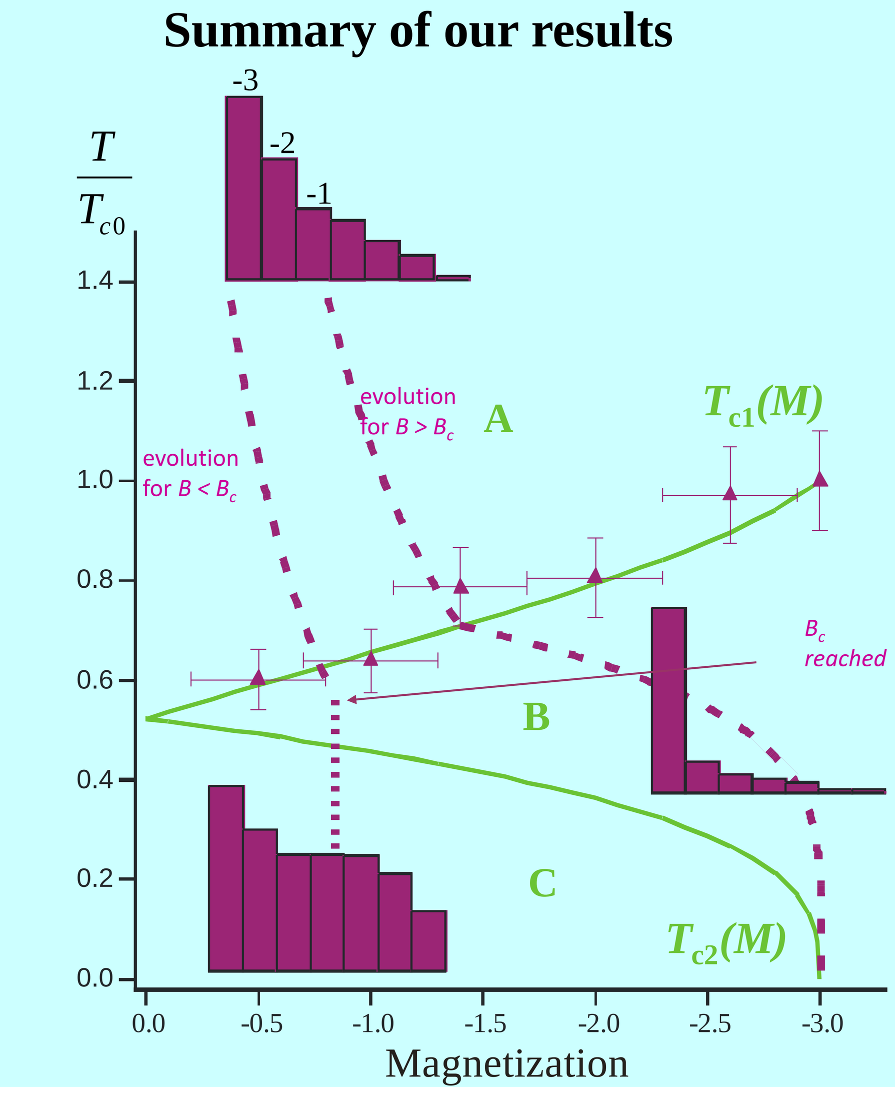
Reduction of the condensed fraction



for T < T_{c2}
BEC in all m_S !

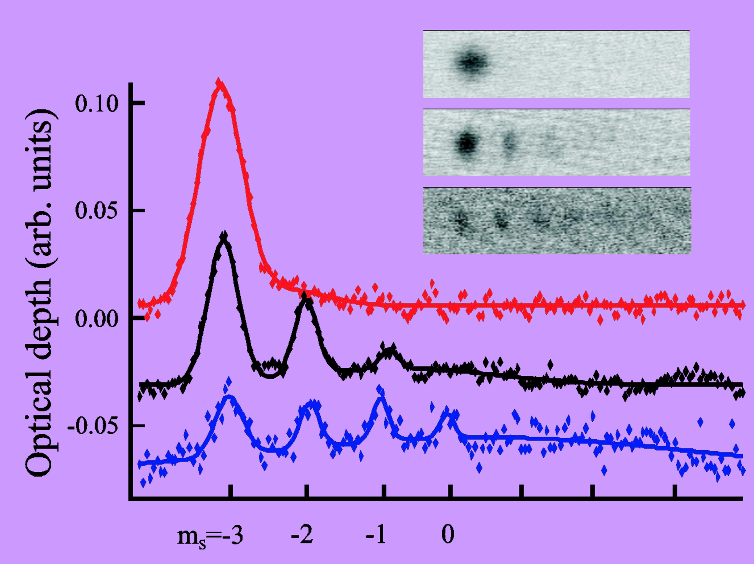
for T_{c2} < T < T_{c1}
BEC only in m_S = -3

Summary of our results



Due to contact interactions, below Bc we have a multicomponent BEC, with free magnetization due to DDIs, behaving almost like a non-interacting BEC with fixed magnetization

Stern Guerlach analysis of the depolarized gas



All components remain Bose condensed

Other results

Other work: we use Bragg scattering to measure the excitation spectrum of the BEC
* at "high B fields": due to DDIs, the speed of sound depends on the orientation of **B** with respect to the one of the momentum transfer - see the poster of Olivier Gorceix on Thursday
* below Bc, we have just measured a dramatic change in the excitation spectrum at low **q**, in the lattice (preliminary results)

Current work: resonant dipolar relaxation in 3D optical lattices
see the poster of Amodsen Chotia on Thursday

Graduate students are welcome !

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