Spontaneous demagnetization of a chromium BEC

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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, dipolar relaxation (inelastic collision) prevents to obtain a BEC in a magnetic trap, and chromium BECs are produced in an optical trap, in the absolute ground state $m_S = -3$: the BEC is polarized. But 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.

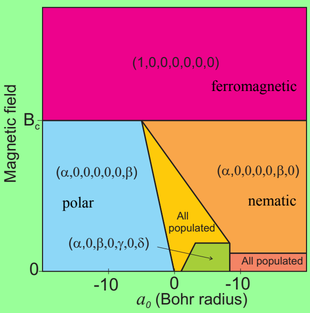
Our work is described in B. Pasquiou et al., Arxiv 1103.4819v1 (accepted at PRL)

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 :

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

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 : $B_c = 10\ \mu$G for Rb (a_2-a_0 small)

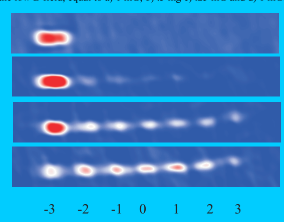
Ref Diener et Ho, PRL **96**, 190405 ; Santos et Pfau, PRL **96**, 190404

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

Demagnetization of the BEC after a quench of the magnetic field

We suddenly reduce the value of the B field from 20 mG 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.



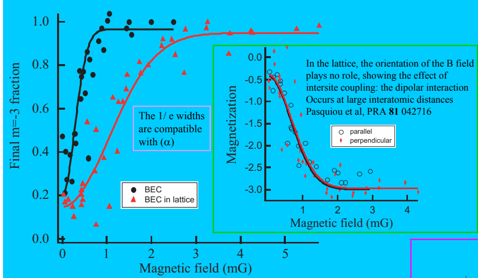
At B =0, the spin populations are: {18+/-9, 18+/-4, 14+/-1.5, 15+/-3, 17+/-3, 12.5+/-4, 6+/-2}

Characteristics of the BEC:
$N_{atoms} = 20000$, $\mu = 4$ 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**.

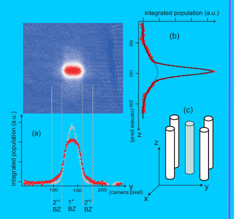
Characteristics of the 1D quantum gases:
- depth = 25 E_R = 120 kHz >> μ = 11 kHz
- peak density = 2.10^{15} cm^{-3}
- larger volume than the BEC (factor 3)

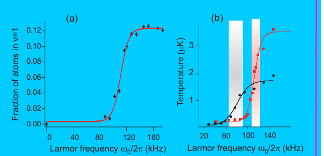
Depolarization as a function of the magnetic field



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 situation differs from our previous work, where we showed that **dipolar relaxation can be suppressed** when B is parallel to the tubes
Pasquiou et al, PRL **106** 015301





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

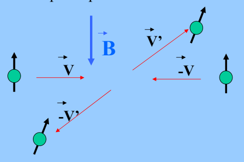
Results:
AC noise = 500 μG, but is screened by the vacuum chamber
DC fluctuations = 100 μ G on a one hour time scale

Dynamics of the demagnetization

The change in the projection of the spin of the BEC cannot be obtained with the contact interaction
The dipole-dipole interaction (DDI) has to come into play

DDI induces spin flip…

Example: dipolar relaxation



…and rotation

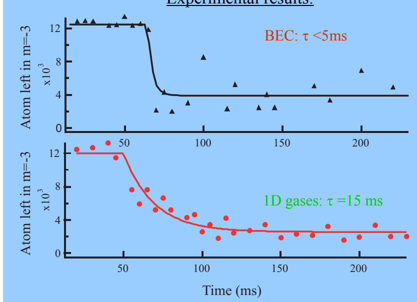
$$[H_{DDI}, S_z + L_z] = 0$$ if the trap has a cylindrical shape

Possible results of a dipolar collision of two m_S=-3 atoms:

$$|-3,-3\rangle \rightarrow \frac{|-2,-3\rangle + |-3,-2\rangle}{\sqrt{2}} \quad \text{or} \quad |-3,-3\rangle \rightarrow |-2,-2\rangle$$

$$M_L = 0 \rightarrow M_L = -1 \qquad M_L = 0 \rightarrow M_L = -2$$

Experimental results:



The evolution is faster in the BEC case !

As explained in our model, the typical timescale for depolarization is set by the magnetic field resulting from the surrounding dipolar atoms, i.e. by the **non-local mean field** due to DDIs

For atoms loaded into an optical lattice, the large increase of the (repulsive) contact mean-field forces the cloud to swell in our Experimental configuration; 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 thus 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 $\Pi_{-2} << 1$.
The dynamics between the ϕ_{-3} and ϕ_{-2} components is then given by:

$$i\hbar \frac{d}{dt}\begin{pmatrix}\phi_{-3}\\ \phi_{-2}\end{pmatrix} = H_{tot}\begin{pmatrix}\phi_{-3}\\ \phi_{-2}\end{pmatrix} \qquad H_{tot} = \begin{pmatrix}H(\vec{r}) & \hbar\ \Gamma\\ \hbar\ \Gamma & H(\vec{r}) + g\ \mu_B\end{pmatrix}$$

with $$\Gamma(\vec{r}) = \gamma \int d^3\vec{r}\, \frac{((x-x') - i(y-y'))(z-z')}{|\vec{r}-\vec{r}'|^5} |\phi_{-3}(\vec{r})|^2 \qquad \gamma = 3S^{3/2}\hbar^2 d^2/\sqrt{2} \qquad d^2 = \mu_0 (g\ \mu_B)^2/4\pi$$

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

Works well for $B < B_{dd}$

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

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

Observation of Einstein de Haas effect (not yet !)

Due to the conservation of the total angular momentum accompanying DDI, **vortices** should emerge in the BEC
(see Kawagushi et al, PRL **96** 080405)

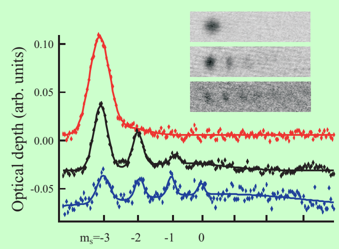
We could not detect vortices in the $m_S = -2$ component.
It is not yet established whether the magnetic field is low enough for such vortices to be observed, nor how long they should survive in our non cylindrical trap in the presence of thermal excitations.

Perspectives

We will next try to observe the rotation necessarily induced by demagnetization, in the spirit of the Einstein-de-Haas effect.
We will also investigate how this rotating system thermalizes at low magnetic fields, to possibly reach quantum nematic (mean-field) phases

Thermodynamics properties of a S=3 spinor condensate with free magnetization

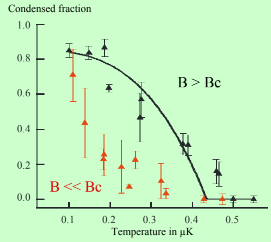
Stern Guerlach (2nd kind) analysis of the depolarized gas



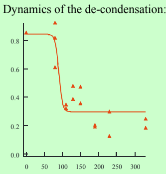
All components remain Bose condensed

Reduction of the condensed fraction

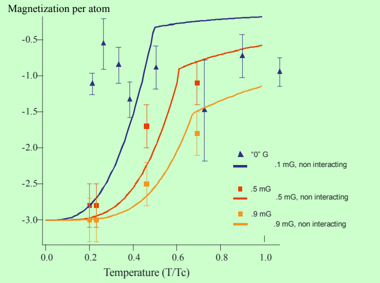
As the spin degree of freedom is unfrozen, condensation gets harder: T_c gets smaller



Dynamics of the de-condensation:



Comparison with prediction for a non interacting S=3 BEC



Difference at low B field !

Conclusion

Some thermodynamical properties are correctly explained in the framework of non interacting spinor thermodynamics

But depolarization cannot be explained in such framework, as without interactions a BEC remain ferromagnetic !

Other results and perspectives

Current work: we use Bragg scattering to measure the excitation spectrum of the chromium 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
* below Bc, we have just measured a dramatic change in the excitation spectrum at low **q**, in the lattice (preliminary results)

Next: load the BEC in 3D optical lattices to observe the EdH effect Long term: obtaining a dipolar Fermi sea (^{53}Cr isotope)

We have a grant for a postdoctoral position starting in September 2011 !

Work supported by : Conseil Régional Ile-de-France (Sesame contract), Ministère de l'Education Nationale et de la Recherche (CPER), European Union (Fonds Européen de Développement Régional) and IFRAF