Spin mixing and protection of ferromagnetism in a spinor dipolar condensate

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We study spin mixing dynamics in a chromium dipolar Bose-Einstein Condensate after tilting the atomic spins by an angle θ with respect to the external magnetic field. Spin mixing is triggered by dipolar coupling but, once dynamics has started, it is mostly driven by contact interactions. For the particular case θ = π/2, an external spin-orbit coupling term induced by a magnetic gradient is required to enable the dynamics. Then the initial ferromagnetic character of the gas is locally preserved, an unexpected feature that we attribute to large spin-dependent contact interactions. [1]

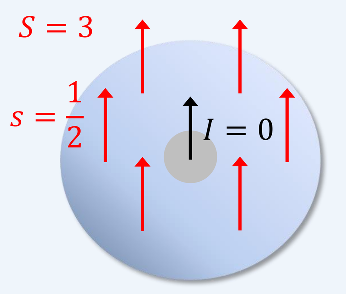
Spin dynamics with ^{52}Cr

Spinor BEC → spin degree of freedom

Total angular momentum: $\vec{F} = \vec{L} + \vec{S} + \vec{I}$

For ^{52}Cr : $L = 0, S = 3$ and $I = 0$ → only spin angular momentum

« Magnetic » atoms
purely electronic spin



Cr (S = 3), Er (J = 7), Dy (J = 10)

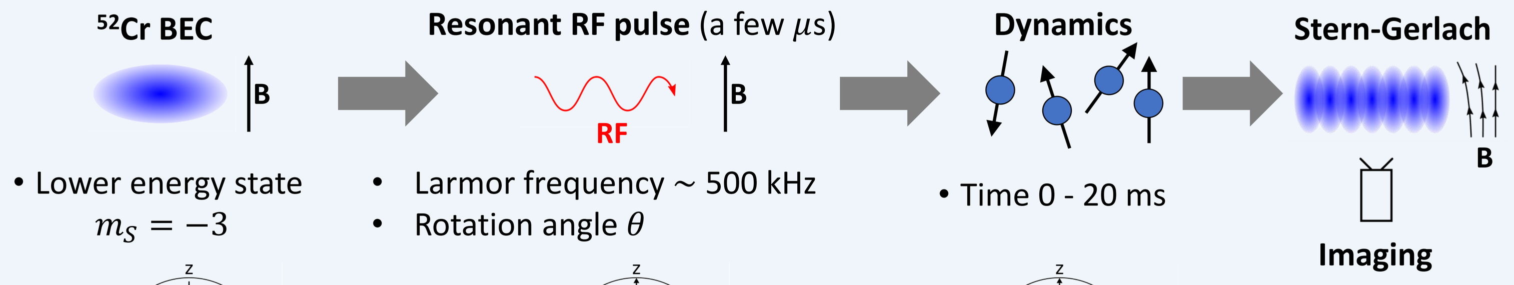
Dipolar quantum gases (Stuttgart, Innsbruck, Stanford, Boulder)

$S = 3$:

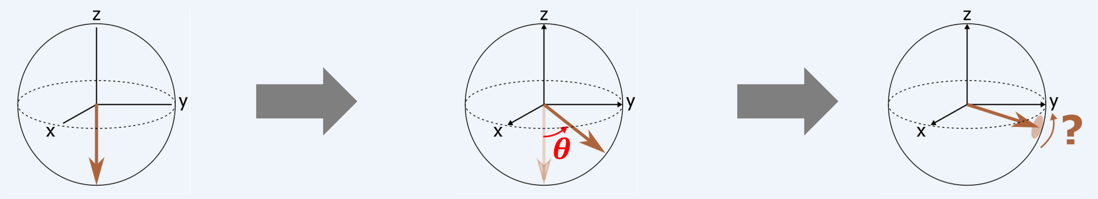
- 7 Zeeman states
- 2-body collisions: $S_{tot} = 0, 2, 4, 6$
- **« Large spin » contact interactions**
- **Strong dipole-dipole interactions (DDI)**

The experiment

Dynamics after an RF pulse



- Lower energy state $m_S = -3$
- Larmor frequency ~ 500 kHz
- Rotation angle θ
- Time 0 - 20 ms

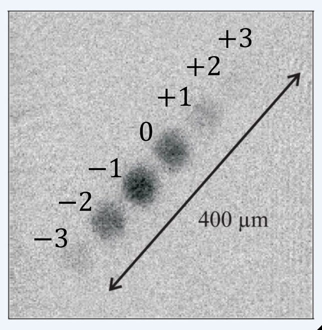


Free evolution

Predictions in a deep lattice [2]:
- Small θ: inhomogeneous classical precession (mean-field)
- $\theta \to \pi/2$: entanglement appear (beyond mean-field effects)

Predictions for a dipolar BEC: dynamics expected with DDI except for the case $\theta = \pi/2$ → no dynamics predicted by mean-field (in absence of magnetic field gradient).

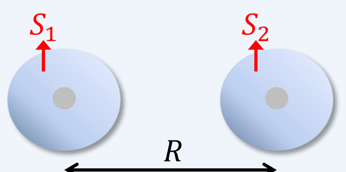
Stern-Gerlach measurement of the number of atoms in each Zeeman state:



Spin dynamics after rotation: three main players

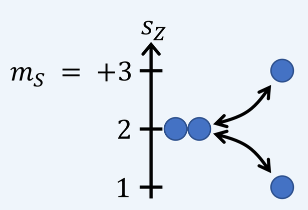
1. Spin dependent contact interactions

2-body collisions: molecular basis



$\vec{S}_{tot} = \vec{S}_1 + \vec{S}_2$

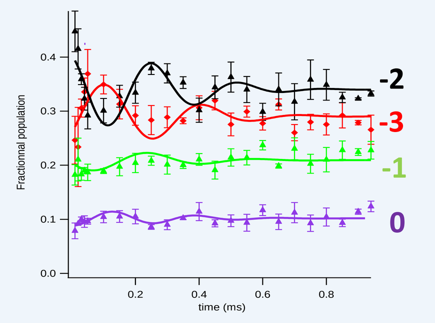
S = 3 → S_{tot} = 0, 2, 4 or 6



$V_{vdW}(R) \propto {}^{1}/_{R^6}$

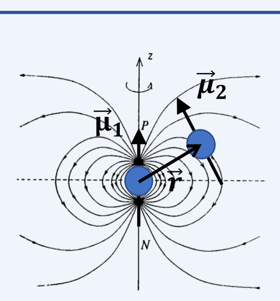
Isotropic and short-range

Pseudo-potential: $V(R) = \frac{4\pi\hbar^2}{m} a_{S_{tot}} \delta(R)$



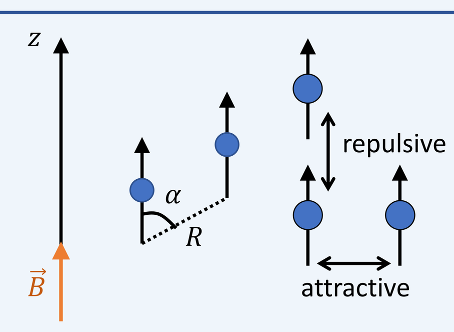
Pairs of atoms in a lattice [3]

2. dipole-dipole interactions



$$\hat{V}_{DDI} = -\hat{\vec{\mu}}_2 \cdot \hat{\vec{B}}_{\hat{\vec{\mu}}_1}(\hat{\vec{r}}) \Rightarrow \boxed{\hat{V}_{DDI} = \frac{\mu_0}{4\pi}(g_S\mu_B)^2 \left[\frac{\hat{\vec{S}}_1 \cdot \hat{\vec{S}}_2}{R^3} - \frac{3\left(\hat{\vec{S}}_1 \cdot \hat{\vec{r}}\right)\left(\hat{\vec{S}}_2 \cdot \hat{\vec{r}}\right)}{R^5}\right]}$$

Anisotropic and long-range



Magnetization conserving terms:

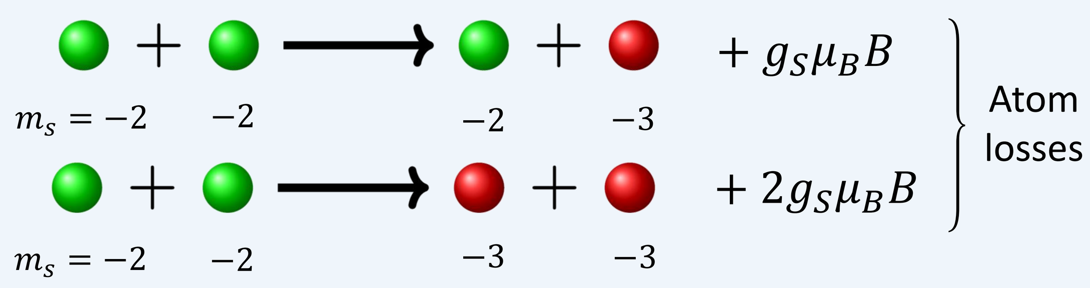
$$\hat{H}_{Ising} = \frac{\mu_0 {\mu_B}^2}{\pi R^3} \hat{S}_{1z}\hat{S}_{2z}\left(1 - 3\frac{\hat{z}^2}{R^2}\right)$$

$$\hat{H}_{exchange} = -\frac{\mu_0 {\mu_B}^2}{4\pi R^3}\left(\hat{S}_{1+}\hat{S}_{2-} + \hat{S}_{1-}\hat{S}_{2+}\right)\left(1 - 3\frac{\hat{z}^2}{R^2}\right)$$

$m_s = -2$ $\quad -2 \quad\quad -3 \quad -1$

Non magnetization conserving terms:

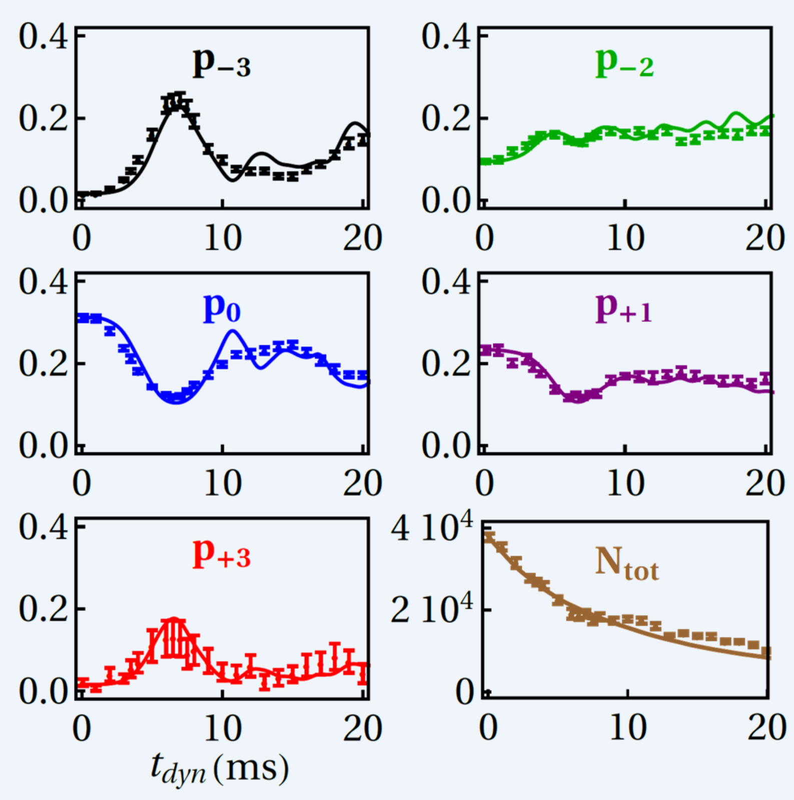
$$\hat{H}_{NMC} = \frac{\mu_0 {\mu_B}^2}{2\pi R^3}\left[-\frac{3}{2}\frac{\hat{z}\hat{r}_-}{R^2}\left(\hat{S}_{1z}\hat{S}_{2+} + \hat{S}_{1+}\hat{S}_{2z}\right) - \frac{3}{2}\frac{\hat{z}\hat{r}_+}{R^2}\left(\hat{S}_{1z}\hat{S}_{2-} + \hat{S}_{1-}\hat{S}_{2z}\right) - \frac{3}{4}\frac{{\hat{r}_-}^2}{R^2}\hat{S}_{1+}\hat{S}_{2+} - \frac{3}{4}\frac{{\hat{r}_+}^2}{R^2}\hat{S}_{1-}\hat{S}_{2-}\right]$$



3. magnetic field gradient: creates inhomogeneity ⇒ spin dynamics (even for $\theta = \pi/2$).

Results

Dots: experimental data
Solid lines: results of our spinor BEC Gross-Pitaevskii numerical simulations (with no free parameter)

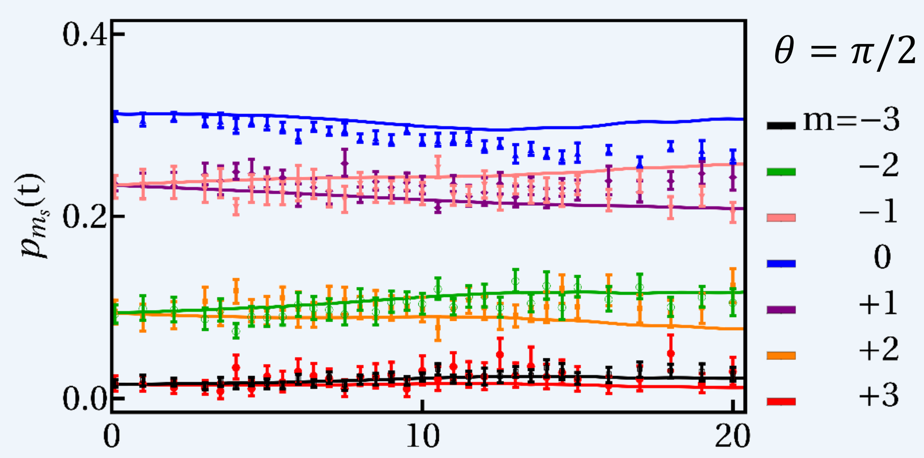


$B_0 = 170\ mG$
$|\vec{\nabla}B| \approx 40 \pm 15\ mG/cm$

→ spin dynamics triggered by MG

→ locally ferromagnetic
(GP simulations from Paolo Pedri and Kaci Kechadi)

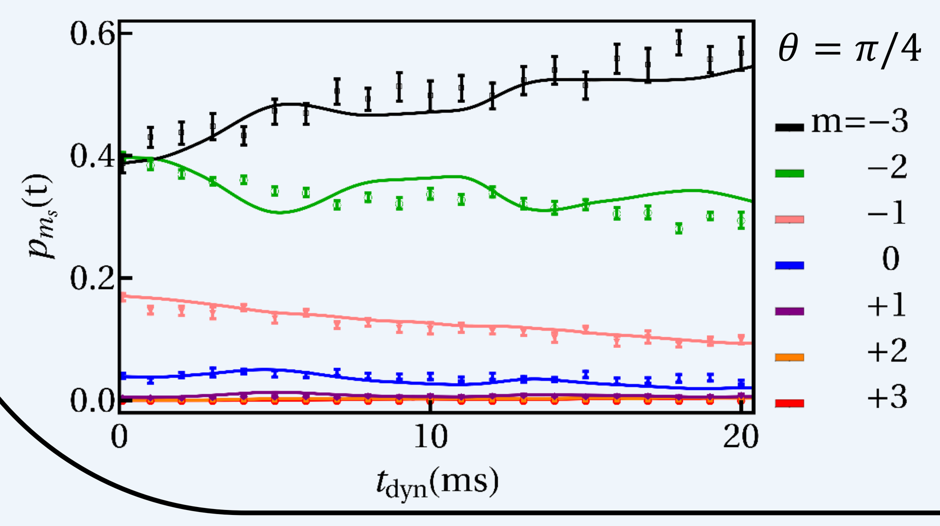
$\theta = \pi/2$



$B_0 = 189\ mG$
$|\vec{\nabla}B| \approx 4 \pm 15\ mG/cm$

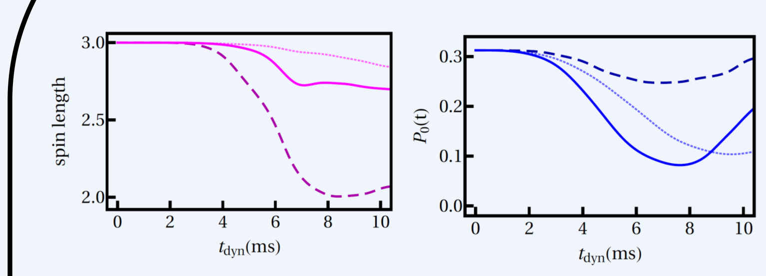
Mean-field prediction verified → no spin dynamics for $\theta = \pi/2$

No spin dynamics → not out of mean-field effects observed



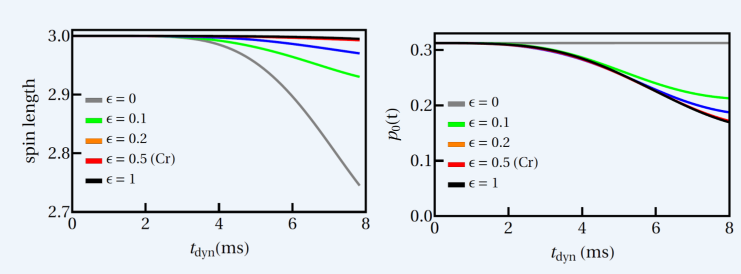
Spin dynamics without MG → DDI witness!

Protection of ferromagnetism



Solid lines: simulation with contact interactions and DDI
Dashed lines: simulation without contact interactions
Dotted lines: simulation without DDI

Simulations show that a local ferromagnetic character is maintained during the dynamics. This comes as a surprise since $a_6 - a_4 > 0$ energetically favors depolarization in the ^{52}Cr BEC. [4]



When we neglect DDI, simulations show that the initial ferromagnetic character is actually protected by spin exchange contact interactions ($\varepsilon = (a_6 - a_4)/a_6$).

Taking the phenomenological assumption that the local spinor remains ferromagnetic, we derive the following evolution of the fractional populations:

$$p_{m_S}(t) = p_{m_S}(0)\left[1 + \frac{1}{2}\left(\frac{g_S\mu_B b}{M R_{TF}}\right)^2 t^4 \left(m_S^2 - \sum_{m'_S} m'^2_S\, p_{m'_S}(0)\right)\right]$$

In this picture, the modification of the local fractional populations due to separation between spin components induced by magnetic field gradient is counterbalanced by spin exchange processes.

Outlook

We will present soon a new work showing that a very different scenario occurs when the ^{52}Cr BEC is loaded in a deep optical lattice.

References

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[3] A. De Paz et al. Phys. Rev. Lett. 111, 185305 (2013)
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