Quantum magnetism with a dipolar BEC

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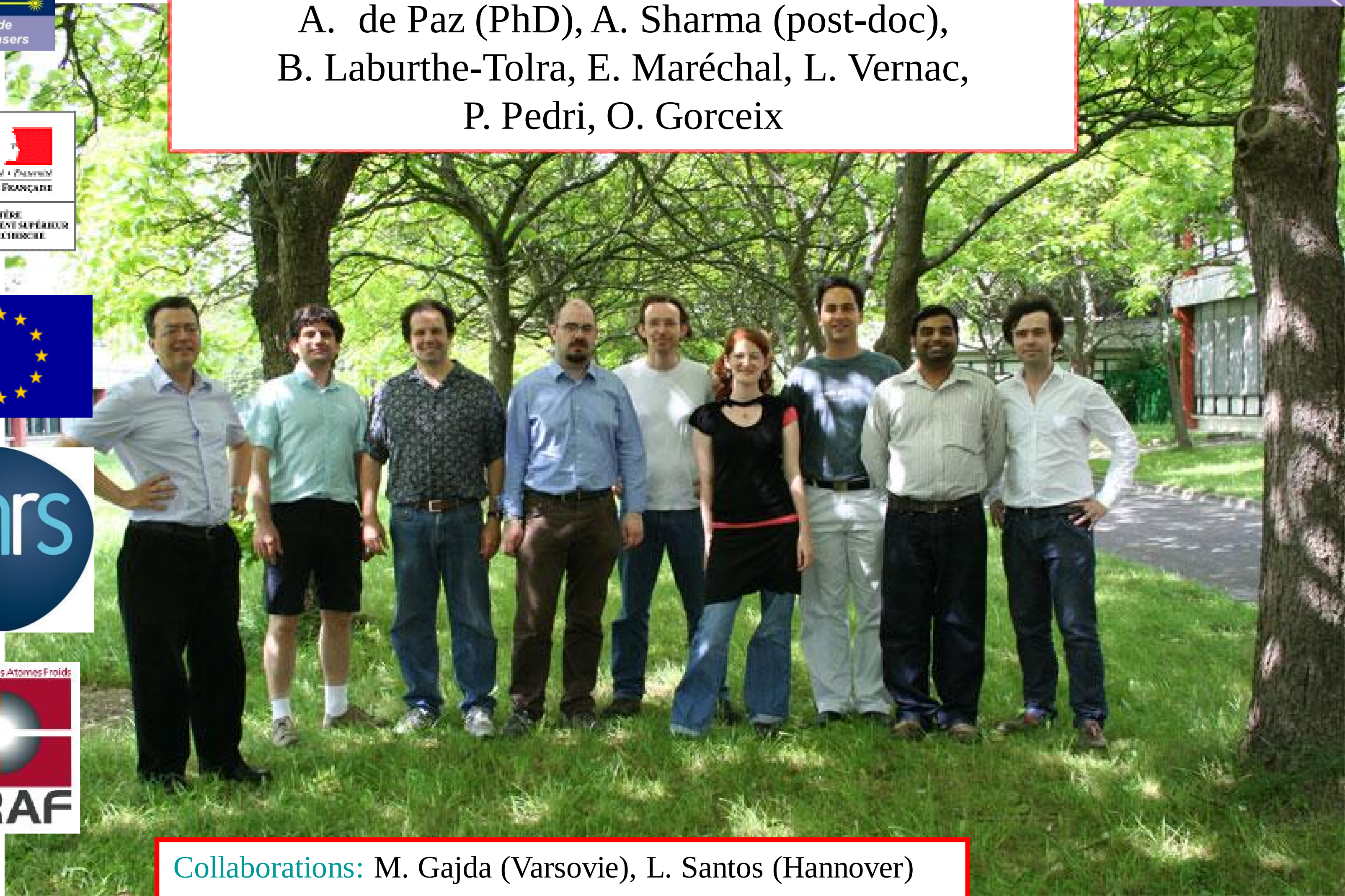
P. Pedri, O. Gorceix

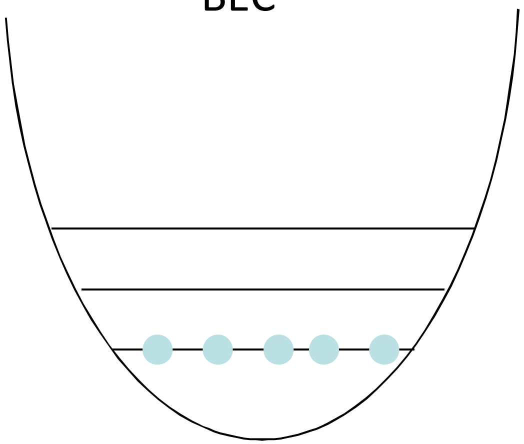


Collaborations: M. Gajda (Varsovie), L. Santos (Hannover)

Former members: A. Chotia, B. Pasquiou

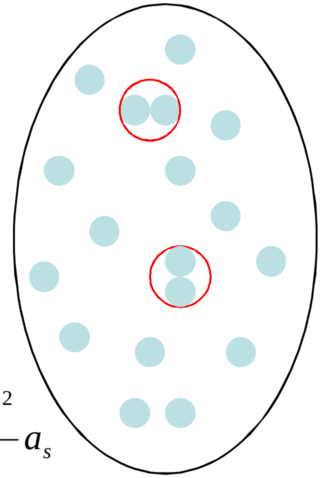
Dipolar Quantum gases

BEC



T_c=few 100 nK

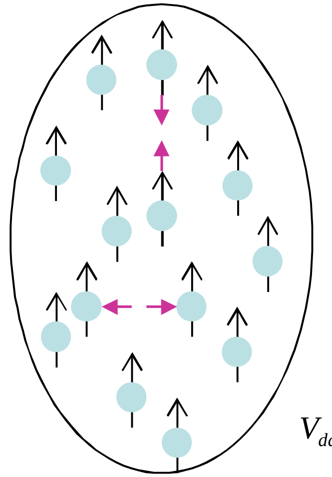
van-der-Waals Interactions



$$g = \frac{4\pi\hbar^2}{m} a_s$$

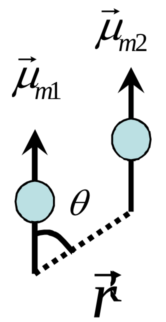
Isotropic
Short range

dipole – dipole interactions



Anisotropic
Long Range

$$\mu_m = J\, g_J \mu_B$$



$$V_{dd}(\vec{r}) = \frac{\mu_0}{4\pi}\mu_m{}^2 \frac{1-3\cos^2\theta}{r^3}$$

comparison of the interaction strength $\varepsilon_{dd} = \frac{\mu_0 \mu_m^2 m}{12\pi\hbar^2 a} \propto \frac{V_{dd}}{V_{VdW}}$ for $\varepsilon_{dd} > 1$ the BEC can become unstable

alcaline $\varepsilon_{dd} << 1$

$\varepsilon_{dd} < 0.01$ for ^{87}Rb

chromium $\varepsilon_{dd} = 0.16$

$\mu_m = 6\mu_B$

erbium

dysprosium $\varepsilon_{dd} \approx 1$

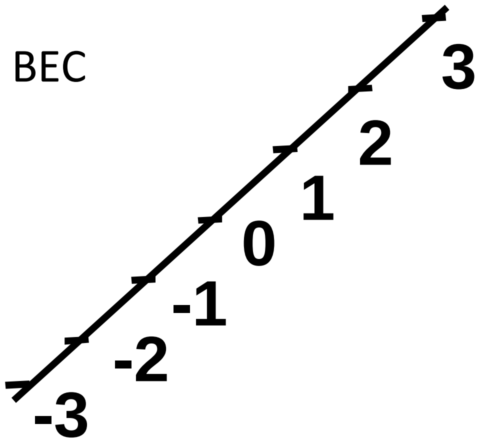
$\mu_m = 10\mu_B$

polar molecules $\varepsilon_{dd} >> 1$

Quantum magnetism with a dipolar BEC

different spin dynamics induced by dipole-dipole interactions

change of Zeeman states populations in a S=3 BEC



magnetization = $\sum_{m_S} P_{m_S} m_S$

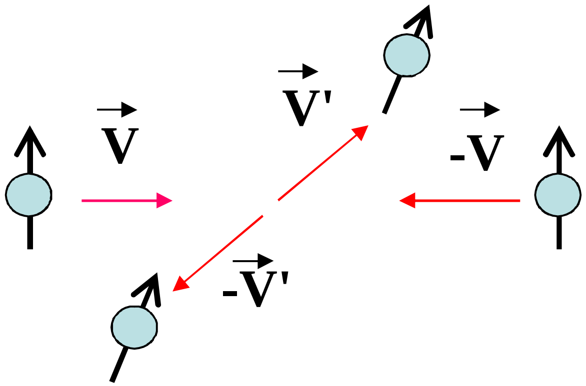
I- demagnetization of the BEC
at low B field

II- dipolar relaxation in a 3D lattice

} change of the magnetization

III- spin exchange in a 3D lattice — constant magnetization

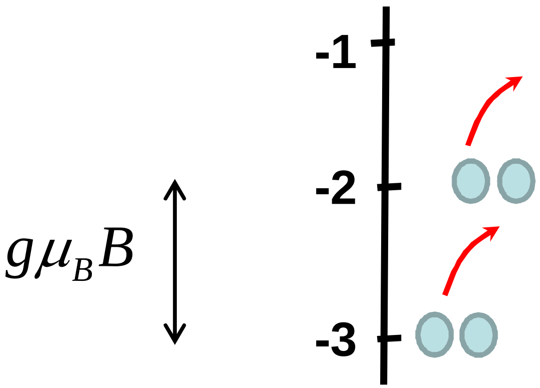
Spin changing collisions



$$\Delta m_S = (m_{s1} + m_{s2})_f - (m_{s1} + m_{s2})_i \neq 0$$

$$E_c^{\ f} = E_c^{\ i} + \Delta E_{magnetic} \qquad \Delta E_{magnetic} = g\mu_B \Delta m_S$$

from the ground state

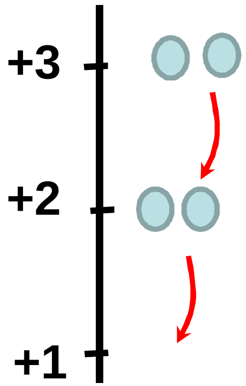


spin changing collisions become possible at low B field

the Cr BEC can
depolarize at low B fields

At low B field the Cr BEC is a S=3 spinor BEC

from the highest energy Zeeman state



dipolar relaxation

after an RF transfer to ms=+3 study of the transfer to the others m_S

rotation induced

$$\Delta m_S + \Delta m_l = 0$$

dipole-dipole interactions induce a spin-orbit coupling

Cr BEC in a 3D optical lattice : coupling between magnetic and band excitations

S=3 spinor gas: the non interacting picture

T_c is lowered

Single component Bose thermodynamics

$$g_J \mu_B B >> k_B T$$

$$N_{th} = N_{tot} - N_c = \sum_{n_x, n_y, n_z} \left(\exp\left[\beta\hbar\left(\omega_x n_x + \omega_y n_y + \omega_z n_z\right)\right] - 1\right)^{-1}$$

$$\beta = 1 / k_B T \qquad k_B T_{c0} = 0.94\ \hbar\overline{\omega}\ N_{at}^{1/3}$$

average trap frequency

apply even if S>0
if no dipole-dipole interactions

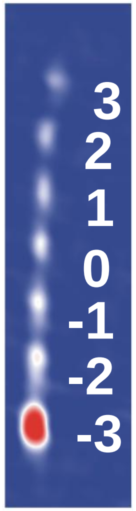
Multi-component Bose thermodynamics

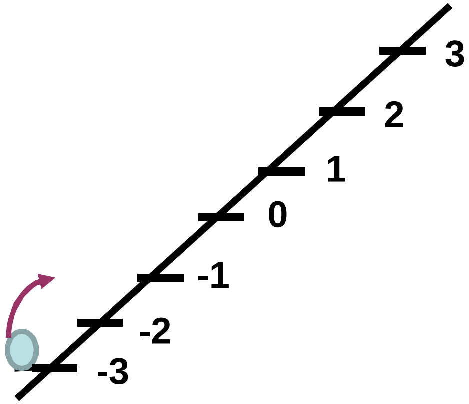
$$g_J \mu_B B \approx k_B T$$

$$N_{th}\left(\beta\ \mu_i\right) = \sum_{n_x, n_y, n_z} \left(\exp\left[\beta\hbar\left(\omega_x n_x + \omega_y n_y + \omega_z n_z\right) + \beta\mu_i \right] - 1\right)^{-1}$$

$$\mu_i = \mu + g_J \mu_B m_{Si} B$$

$$T_c \underset{B \to 0}{\rightarrow} \frac{1}{(2S+1)^{1/3}} T_{c0}$$

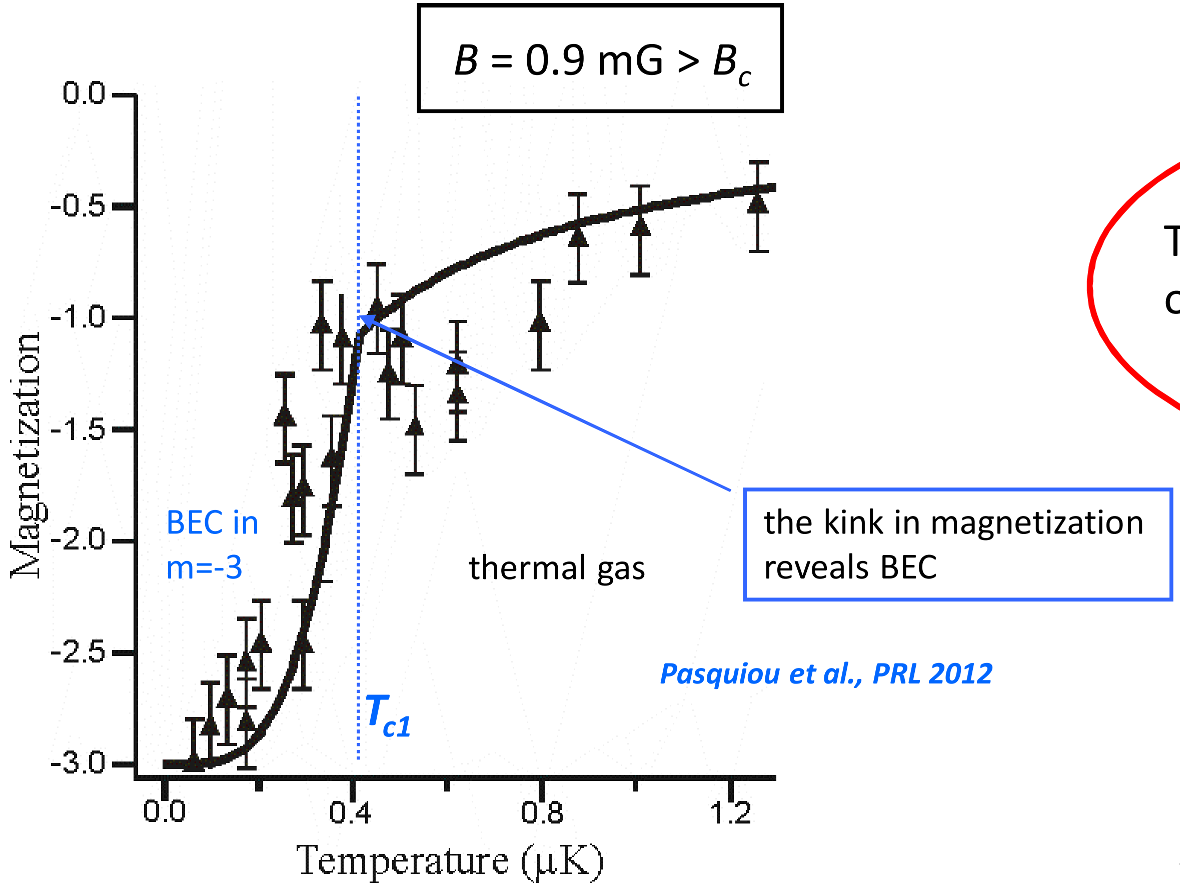




at low B field excited states are thermally populated
thanks to dipole-dipole interactions

Our results: magnetization versus T

$B > B_c$



Pasquiou et al., PRL 2012

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

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

Solid line: results of theory without interactions and free magnetization

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)

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

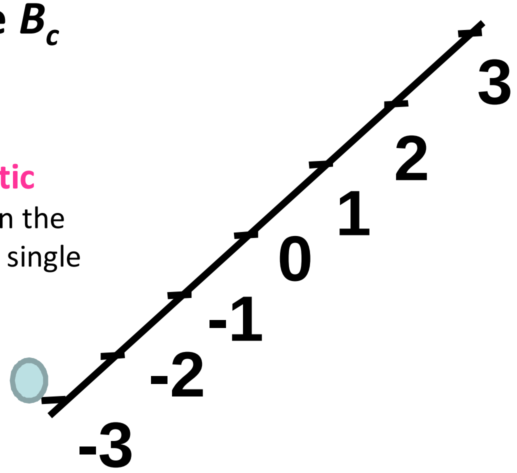
$$B \to 0 \quad \swarrow \quad \frac{1}{(2S+1)^{1/3}} T_{c0} < T_{c1} < T_{c0} \quad \searrow \quad B \to \infty$$

S=3 Spinor physics below B_c: emergence of new quantum phases

Above B_c

the BEC is ferromagnetic

i.e. polarized in the lowest energy single particle state



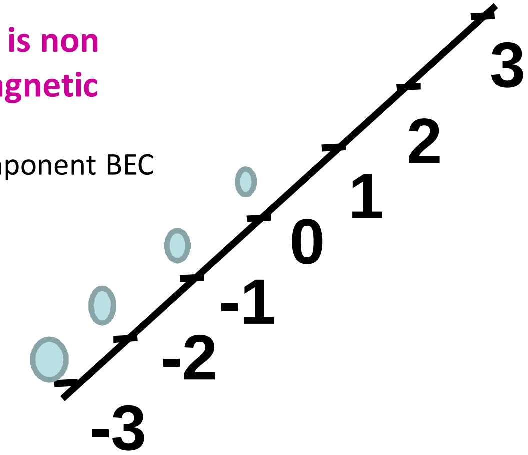
All the atoms in m_S= -3 interactions only in the molecular potential S_{tot}= 6 because $m_{s\,tot}$ = -6

The repulsive contact interactions set by a_6

Below B_c

the BEC is non ferromagnetic

i.e. it is a multicomponent BEC



If atoms are transferred in m_S= -2 then they can interact also in the molecular potential S_{tot}= 4 because $m_{s\,tot}$ = -4

The repulsive contact interactions are set by a_6 and a_4

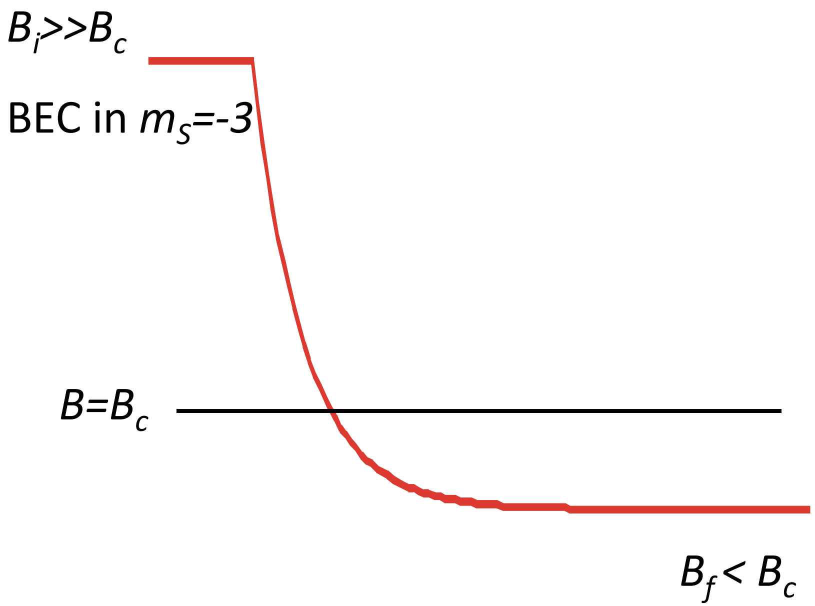
As $a_6 > a_4$, it costs no energy at B_c to go from m_S=-3 to m_S=-2 : the stabilization in interaction energy compensates for the Zeeman energy excitation

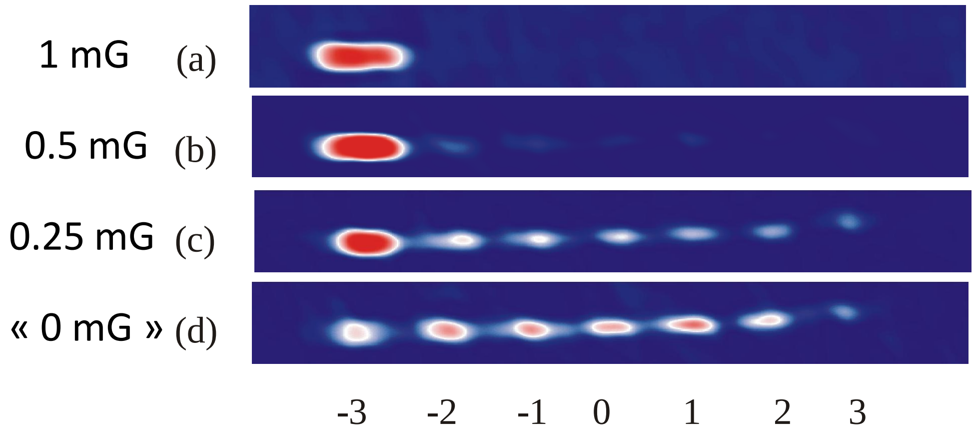
$$g_J \mu_B B_c = 0.7 \frac{2\pi\, \hbar^2 (a_6 - a_4)}{m} n_0$$

S=3 Spinor physics below B_c: spontaneous demagnetization of the BEC

Experimental procedure:

Rapidly lower magnetic field below B_c
measure spin populations with **Stern Gerlach** experiment





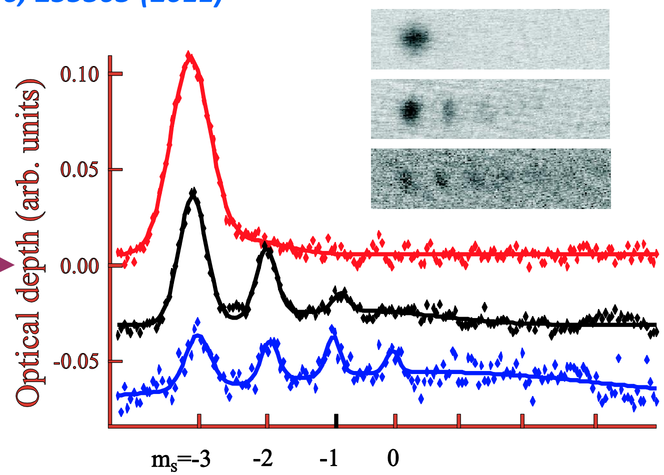
Pasquiou et al., PRL 106, 255303 (2011)

Magnetic field control
dynamic lock, fluxgate sensors
reduction of 50 Hz noise fluctuations
feedback on earth magnetic field, "elevators"

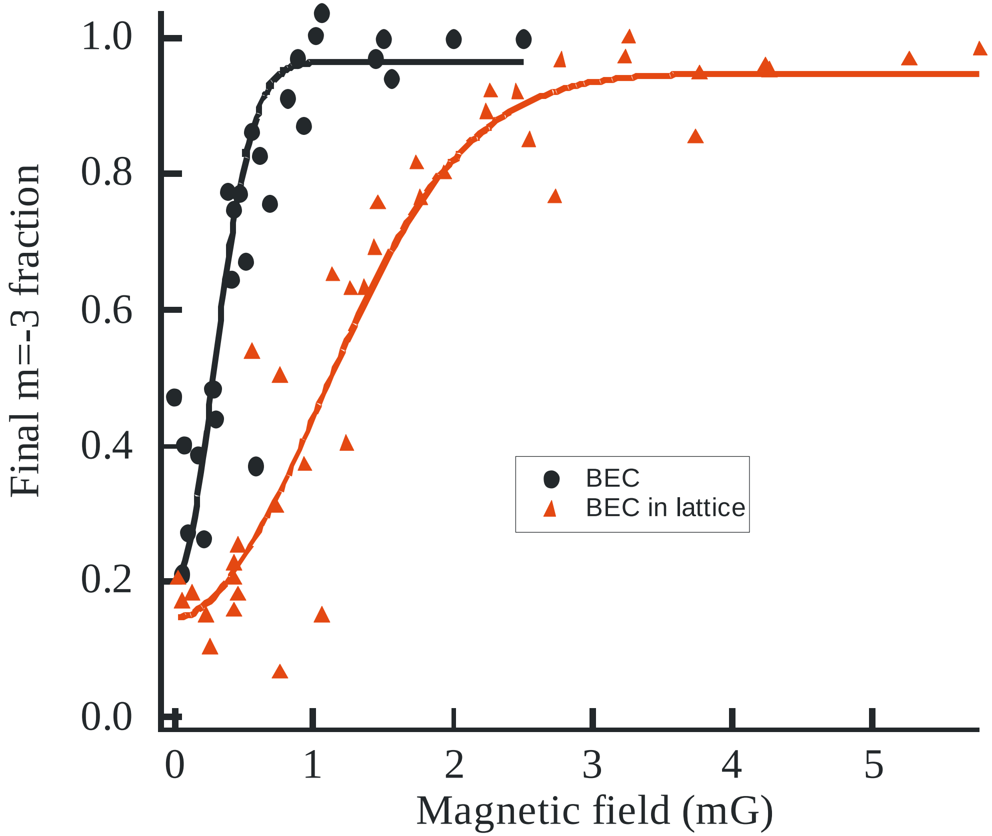
Performances: 0.1 mG stability
without magnetic shield,
up to 1 Hour stability

BEC in all Zeeman components !

+ $N_{thermal}$ << N_{tot}



S=3 Spinor physics below B_c: local density effect



$$g_J \mu_B B_c \approx \frac{2\pi\hbar^2 n_0 \left(a_6 - a_4\right)}{m}$$

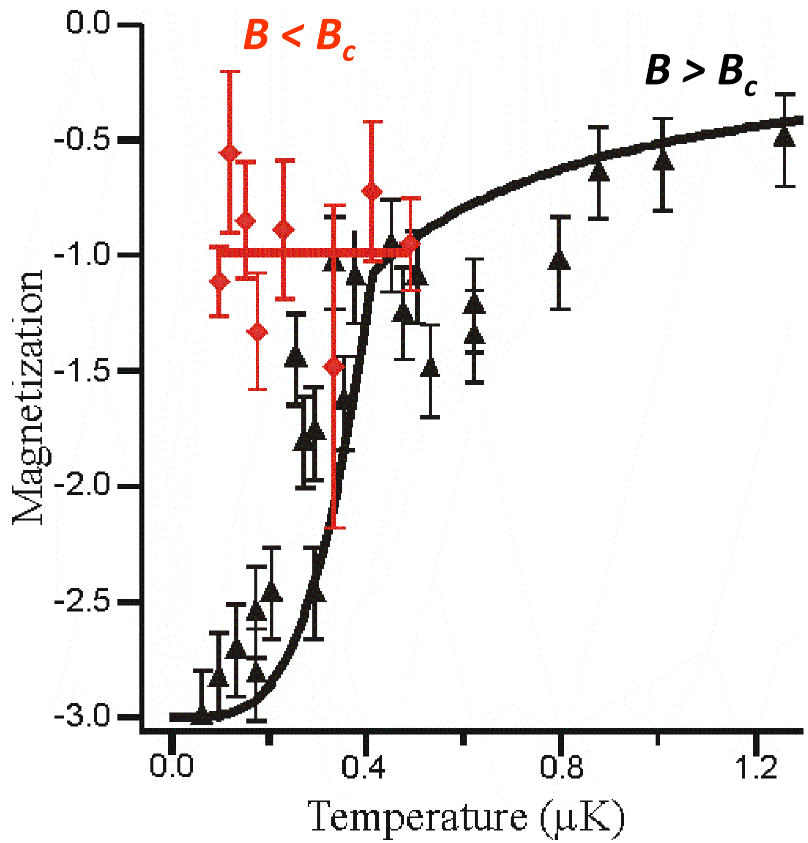
	3D BEC	1D Quantum gas
B_c expected	0.26 mG	1.25 mG
1/e fitted	0.3 mG	1.45 mG

Pasquiou et al., PRL 106, 255303 (2011)

B_c depends on density

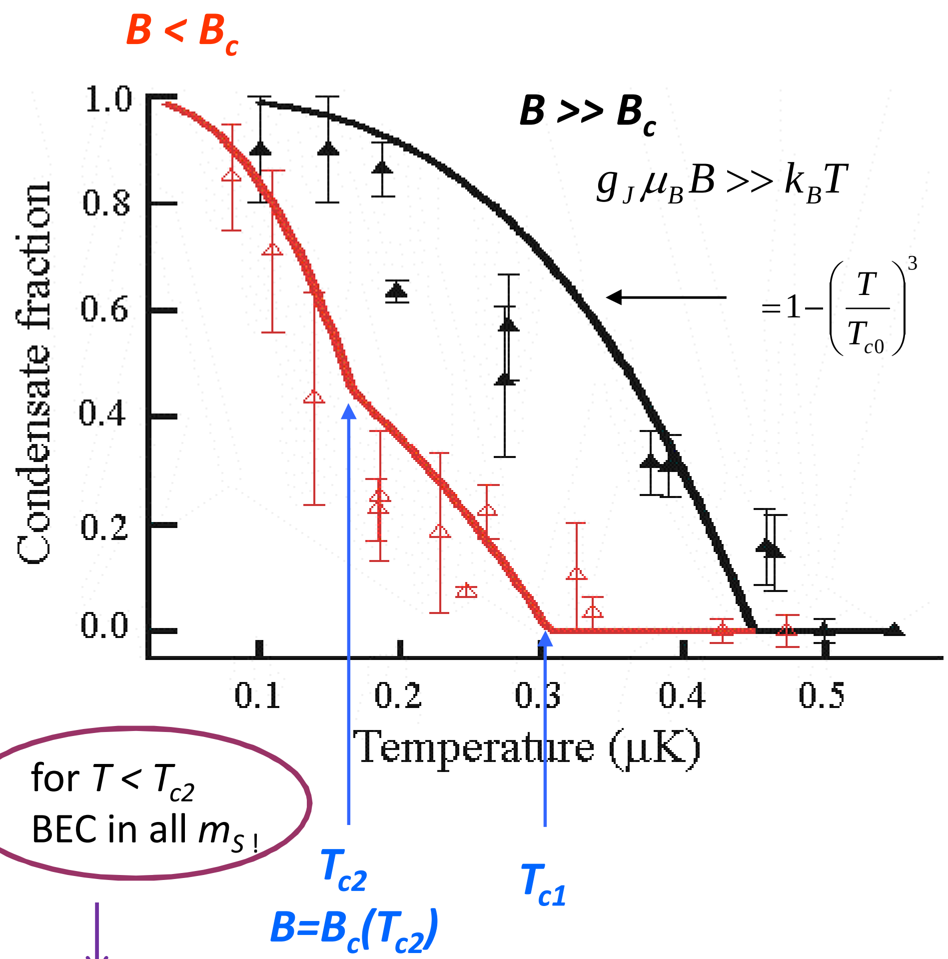
2D Optical lattices increase the peak density by about 5

S=3 Spinor physics below B_c: thermodynamics change



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



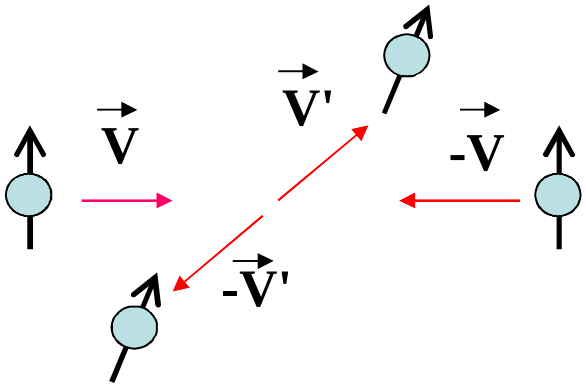
for $T < T_{c2}$
BEC in all m_S!

hint for double phase transition

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

Pasquiou et al., PRL (2012)

Spin changing collisions



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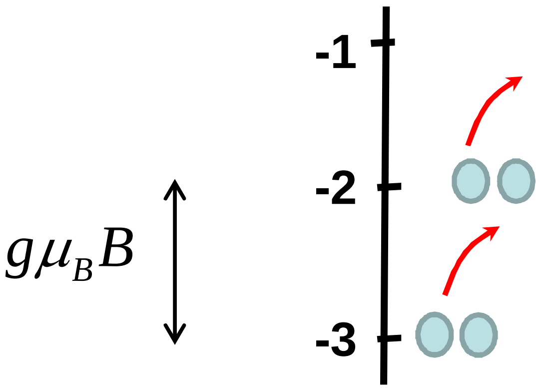
$$E_c^{\ f} = E_c^{\ i} + \Delta E_{magnetic} \qquad \Delta E_{magnetic} = g\mu_B \Delta m_S$$

from the ground state



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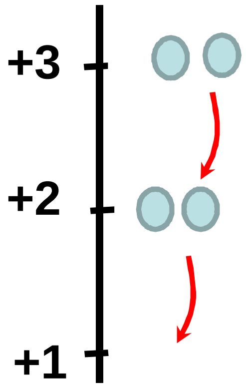


dipolar
relaxation

after an RF transfer to ms=+3 study of the transfer to the others m_S

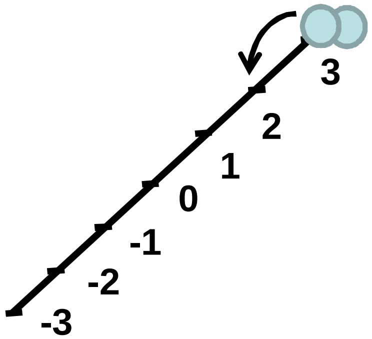
rotation induced

$$\Delta m_S + \Delta m_l = 0$$

dipole-dipole interactions
induce a spin-orbit coupling

Cr BEC in a 3D optical lattice : coupling between magnetic and band excitations

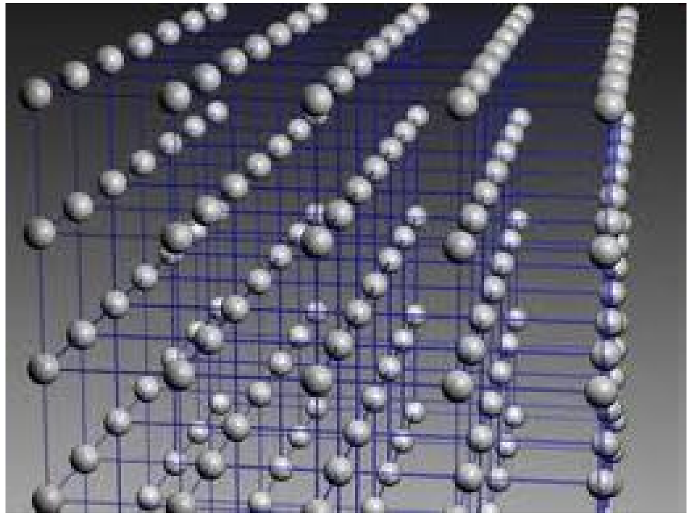
Dipolar Relaxation in a 3D lattice



kinetic energy gain

$$|+3,+3\rangle \xrightarrow{(1)} \frac{|+3,+2\rangle + |+2,+3\rangle}{\sqrt{2}} \qquad \Delta E_c^{(1)} = g\mu_B B$$

$$\xrightarrow{(2)} |+2,+2\rangle \qquad \Delta E_c^{(2)} = 2g\mu_B B$$

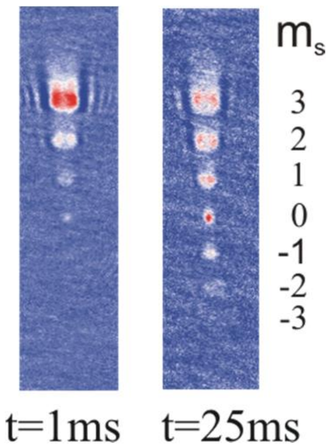


E_c is quantized

dipolar relaxation is possible if:

$$\Delta E_c^{(i)} = \hbar\left(n_x\omega_x + n_y\omega_y + n_z\omega_z\right)$$

(and selection rules)



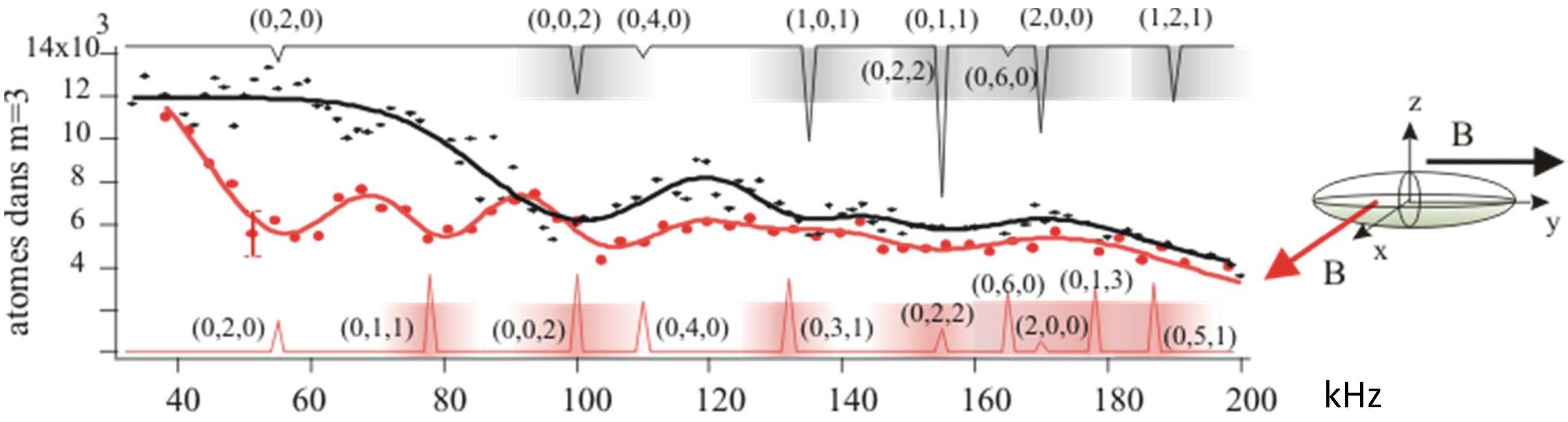
we observe that spin populations change when :

$$\Delta E_c < U_{lattice}$$

Dipolar relaxation in a 3D lattice - observation of resonances

n_x, n_y, n_z

$$\omega_x = 170, \omega_y = 55, \omega_z = 100 \ (2\pi) kHz$$



$g_S \mu_B B$ (Larmor frequency)

1 mG = 2.8 kHz

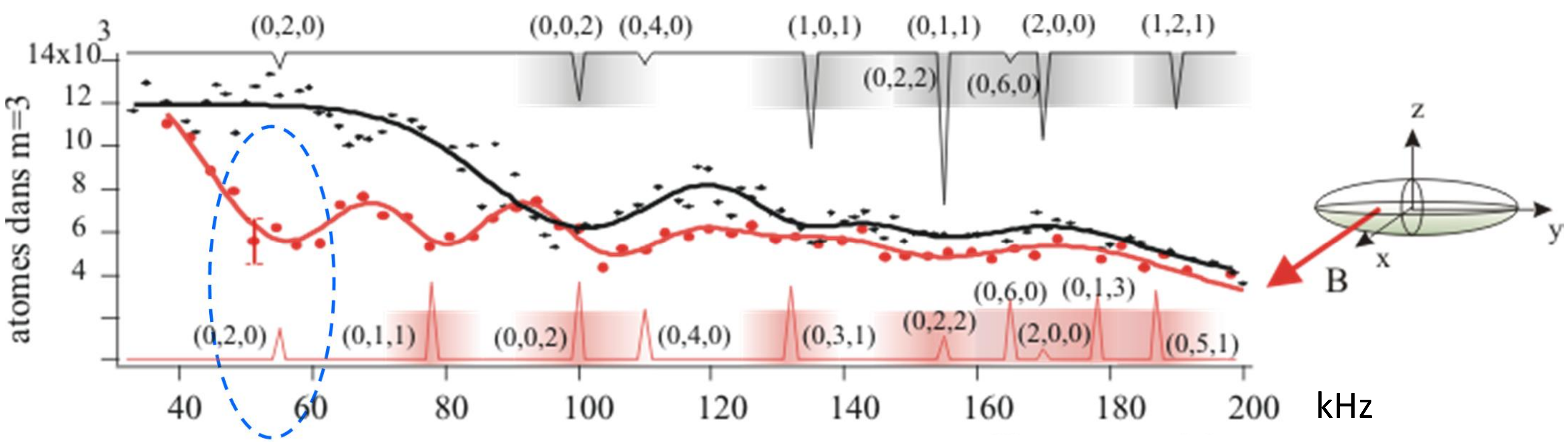
width of the resonances:
tunnel effect +
field, lattice fluctuations

$$|+3,+3\rangle \otimes |0,0,0\rangle \rightarrow \underset{\frac{|+3,+2\rangle + |+2,+3\rangle}{\sqrt{2}}}{|2,2\rangle} \otimes |n_x, n_y, n_z\rangle$$

tunnel effect minimal in an excited states along Oy

$\longrightarrow$ study of the lowest resonance

Dipolar relaxation in a 3D lattice – study of the first resonance



$2g_S\mu_B B = 2\hbar\omega_y$

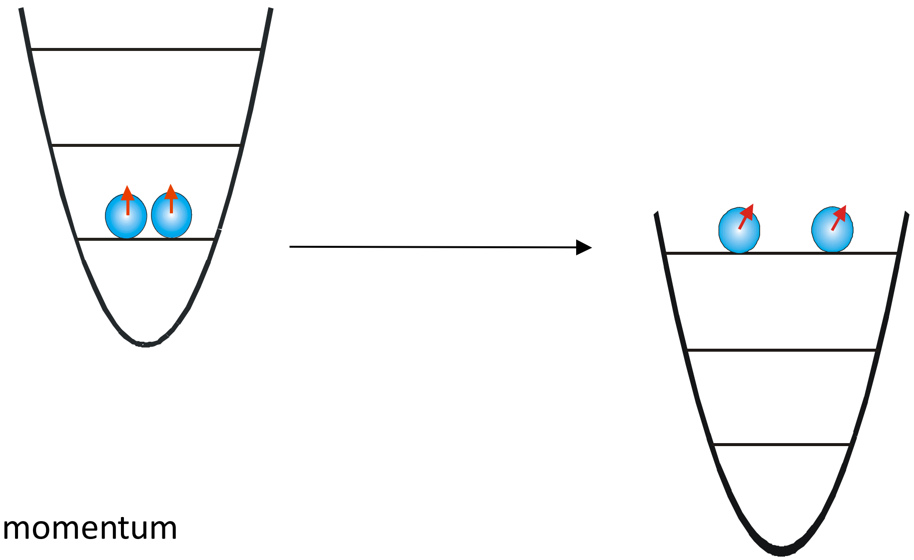
$g_S\mu_B B$

Initial

$|3,3\rangle \otimes |0,0,0\rangle$

spin state

pair orbital momentum

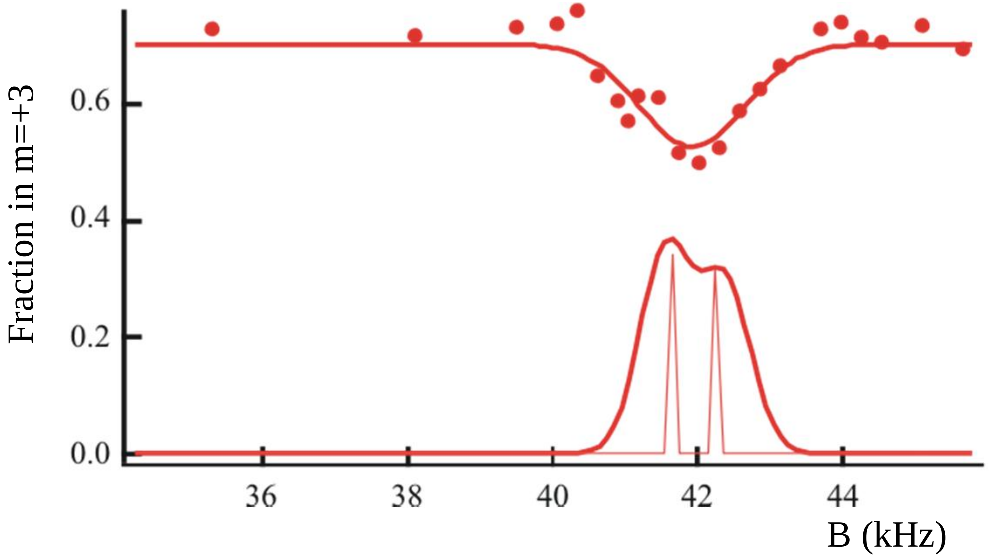


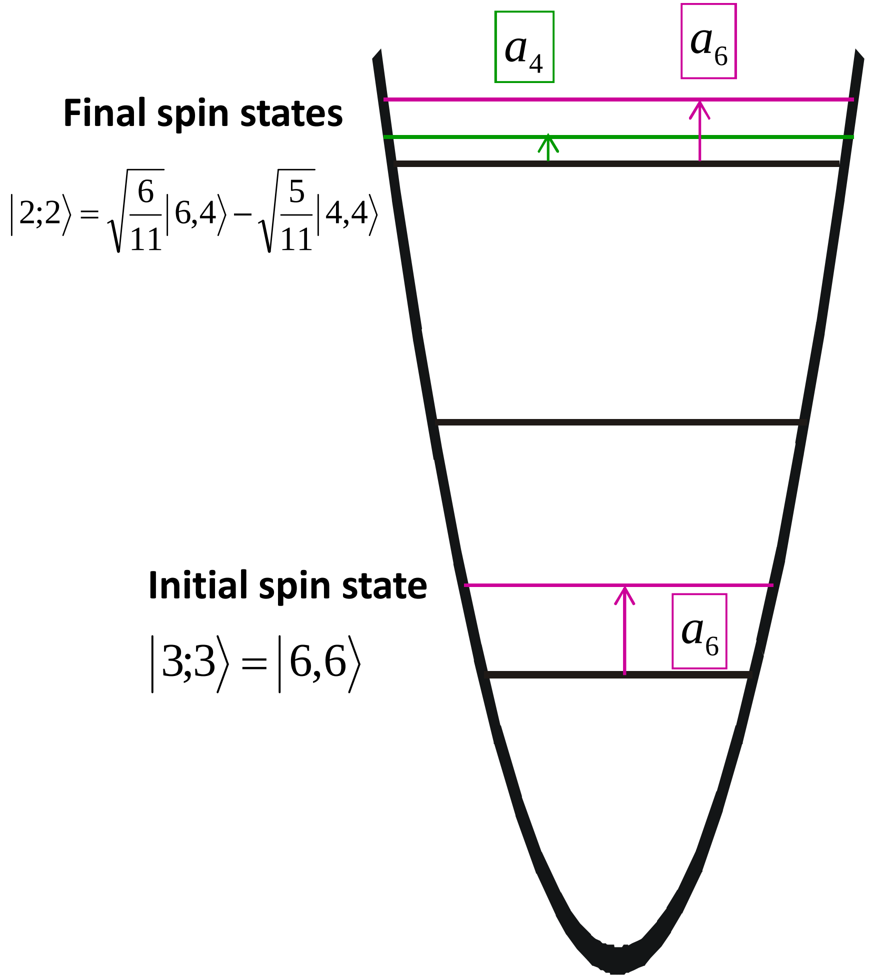
Final

$|2,2\rangle \otimes |0,2,0\rangle$

energy substructure related to onsite contact interactions

Dipolar relaxation in a 3D lattice – effect of onsite contact interactions

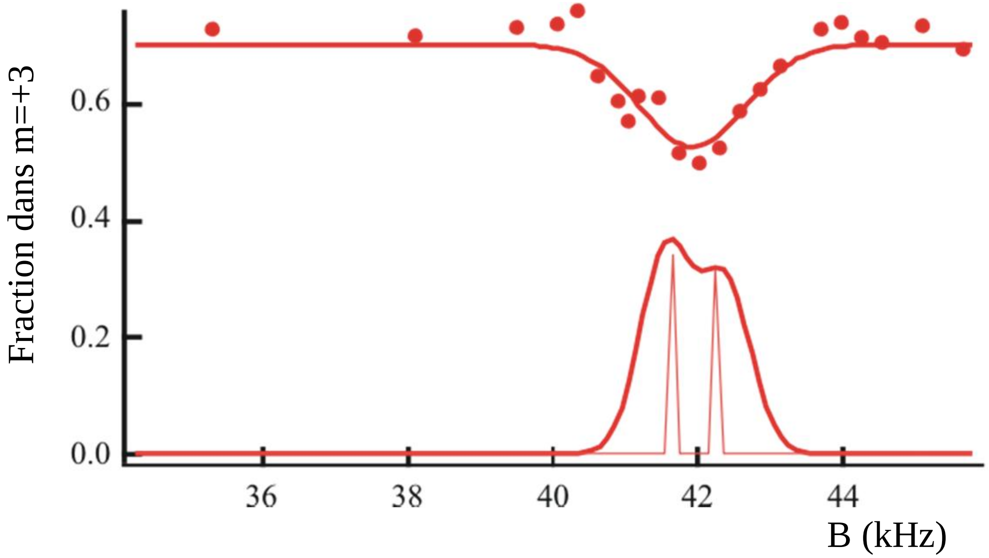




good agreement between theory for
two atoms per site and experiment
both for the shape and position of the resonance

our limit: lattice fluctuations

Dipolar relaxation in a 3D lattice – effect of onsite contact interactions



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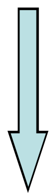
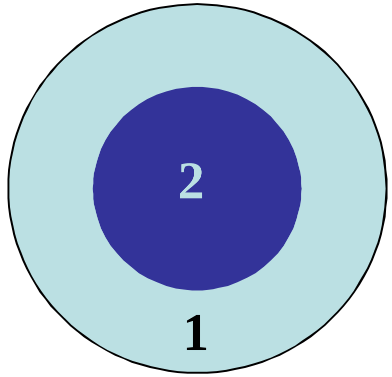
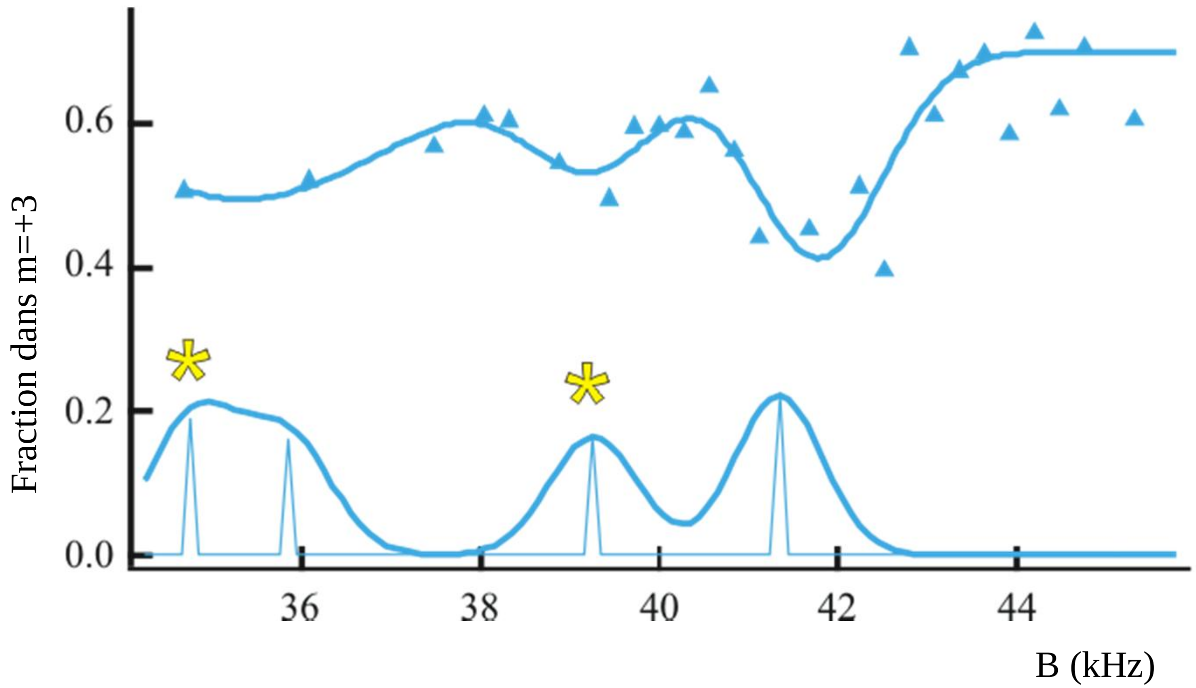


test of the Mott distribution

atomic distribution expected for an adiabatic loading of the 3D lattice (25 E_r)



Production of intricated states with a fast lattice loading



for a **diabatic** loading,
sites with 3 atoms
(or more) are expected

A. de Paz et al., (ArXiv december 2012)

Theory for 3 atoms per site:
4 resonances expected
(4 different energies in the final state)

good agreement between experiment
and theory for three atoms per site

→

"few-body" physics
production of intricated 3 body states

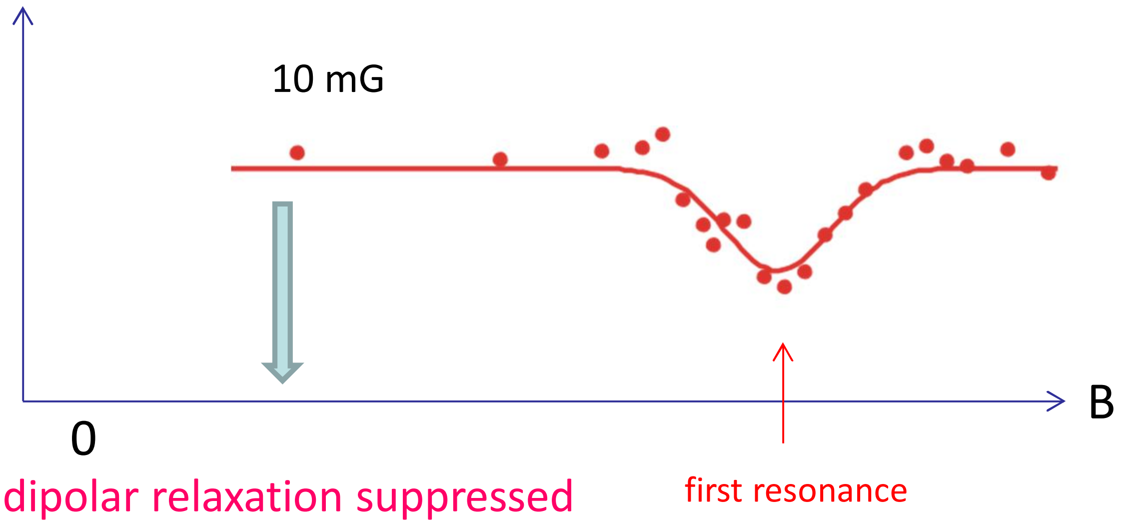
$$|3,3,3\rangle \otimes |0,0,0\rangle \rightarrow \sum |2,2,3\rangle \otimes |2,0,0\rangle$$

spin orbit

↓

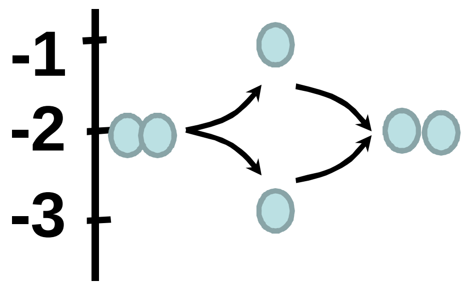
probe of the atomic distribution in the lattice

Spin exchange dynamics in a 3D lattice

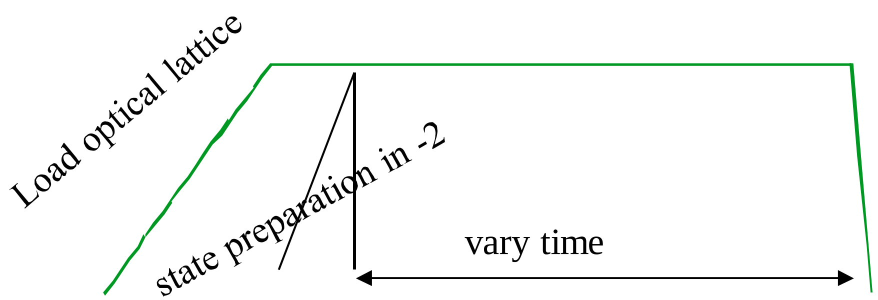


dipolar relaxation suppressed
evolution at constant magnetization

spin exchange from -2



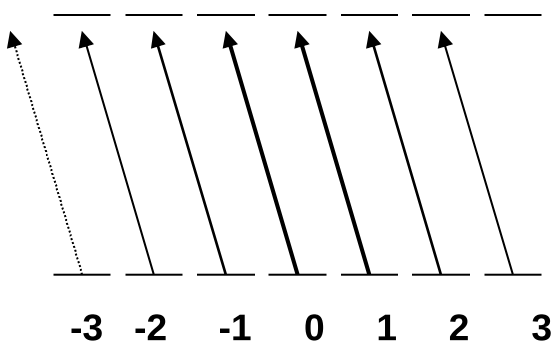
experimental sequence:



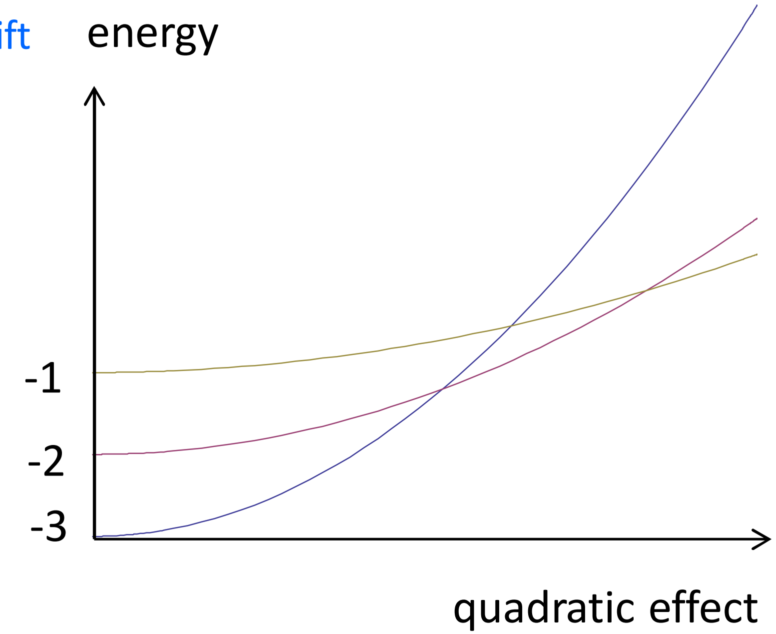
Preparation in an atomic excited state

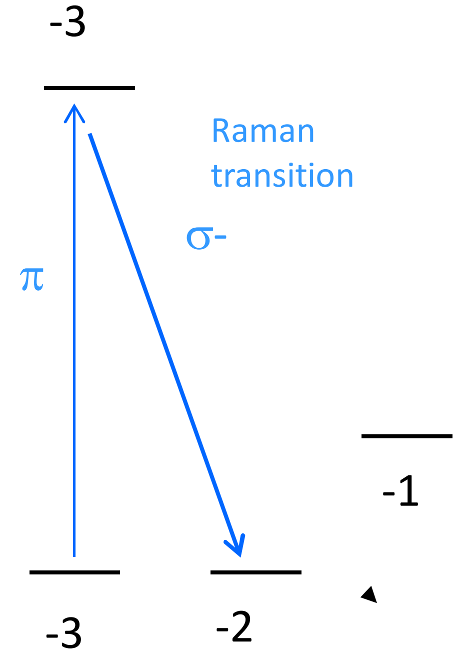
m_S = -2

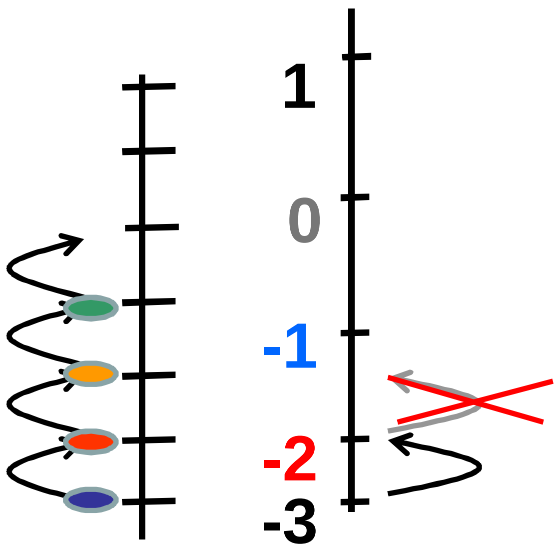
creation of a quadratic light shift

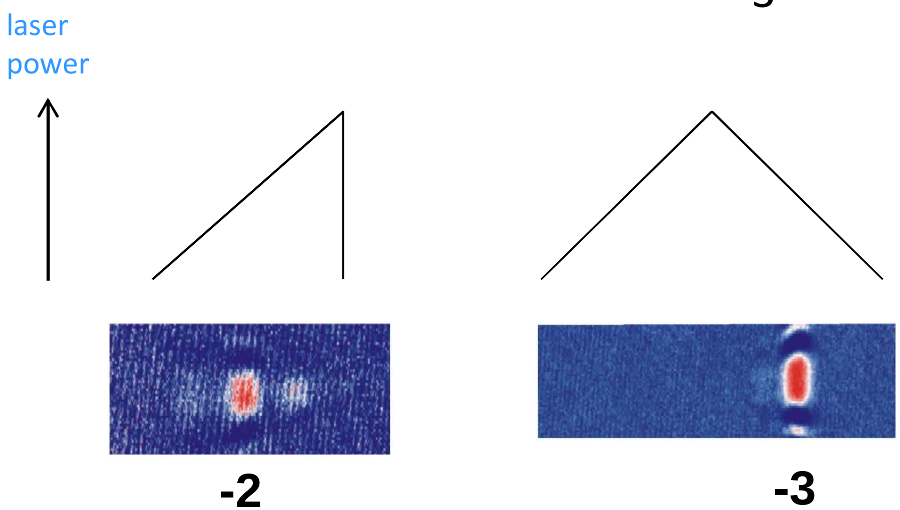


A σ- polarized laser
Close to a J→J transition
(100 mW 427.8 nm)







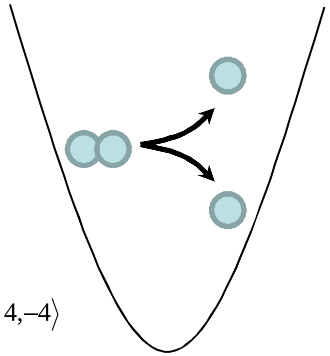


transfer in -2 ~ 80%

transfer adiabatic

Different Spin exchange dynamics in a 3D lattice

Contact interaction (intrasite)

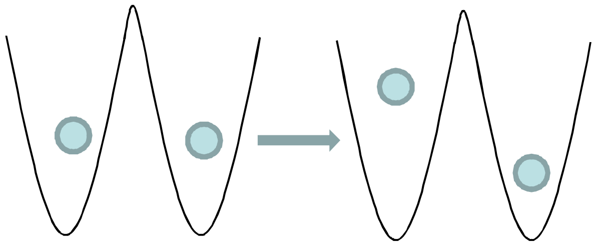


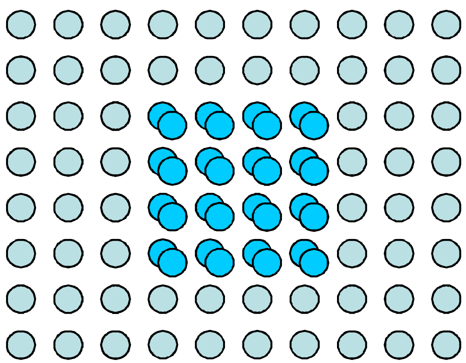
$$|-2;-2\rangle = \sqrt{\frac{6}{11}}|6,-4\rangle - \sqrt{\frac{5}{11}}|4,-4\rangle$$

Dipole-dipole interaction (intersite)

$$\hat H_{dd} = \hat S_{1z}\hat S_{2z} - \frac{1}{4}\left(\hat S_{1+}\hat S_{2-} + \hat S_{1-}\hat S_{2+}\right)$$

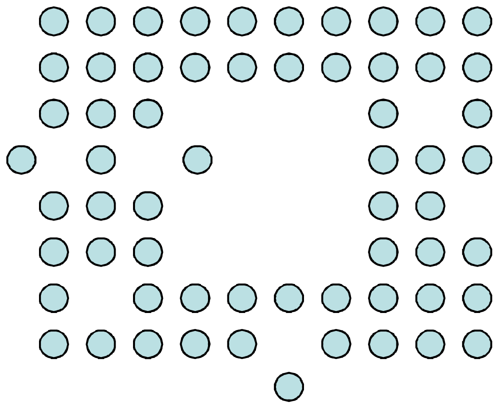
without spin changing term





dipolar relaxation with

$$\Delta E_c >> U_{lattice}$$

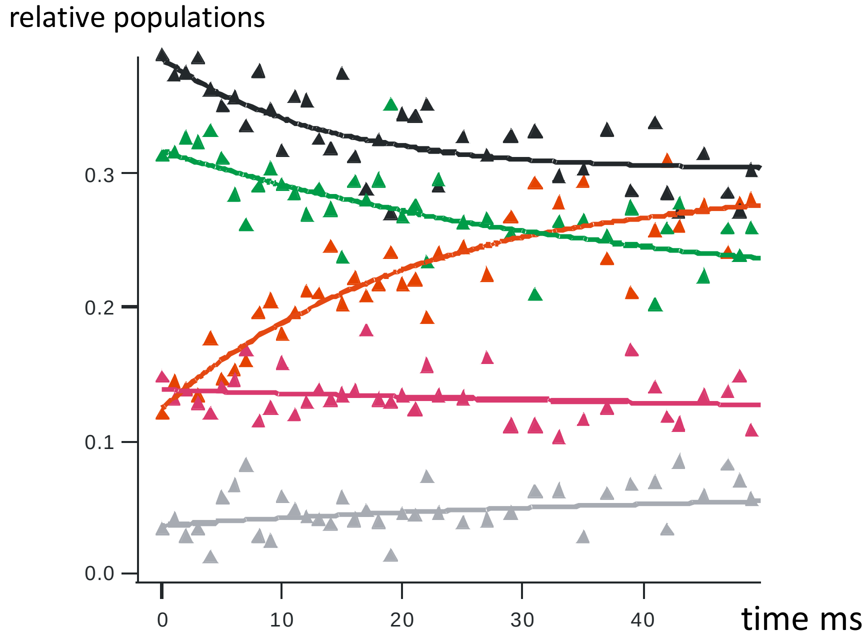


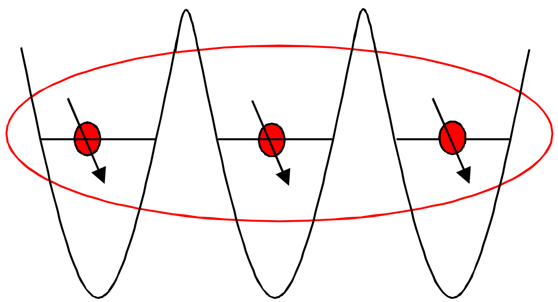
expected Mott distribution

doublons removed = only singlons

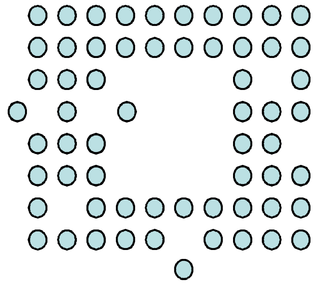
Spin exchange dynamics in a 3D lattice: with only singlons

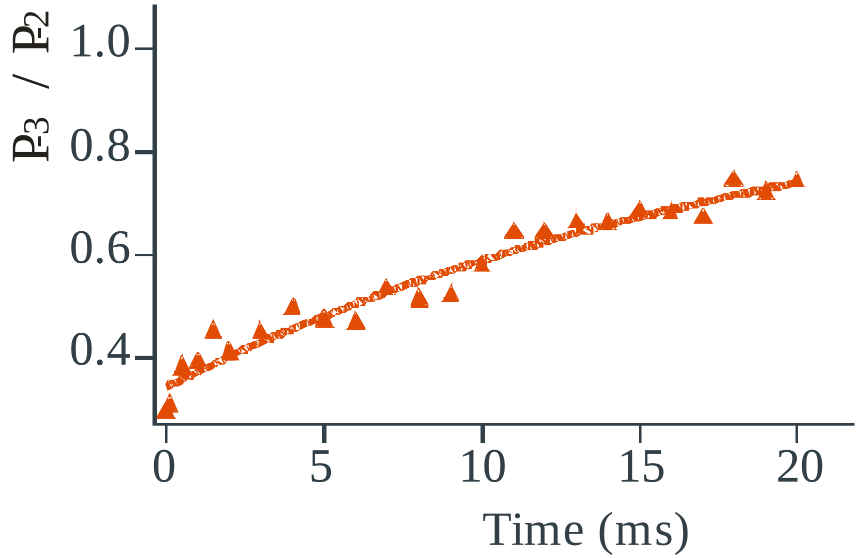
the spin populations change!





Proof of intersite dipolar coupling





comparison with a plaquette model (Pedri, Santos)
3*3 sites containing one atom – work in progress
quadratic light shift and tunneling taken into account

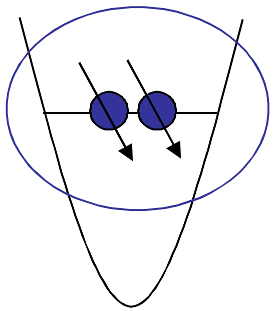
Spin exchange dynamics in a 3D lattice with doublons at short time scale

initial spin state

$$|-2;-2\rangle = \sqrt{\frac{6}{11}}|6,-4\rangle - \sqrt{\frac{5}{11}}|4,-4\rangle$$

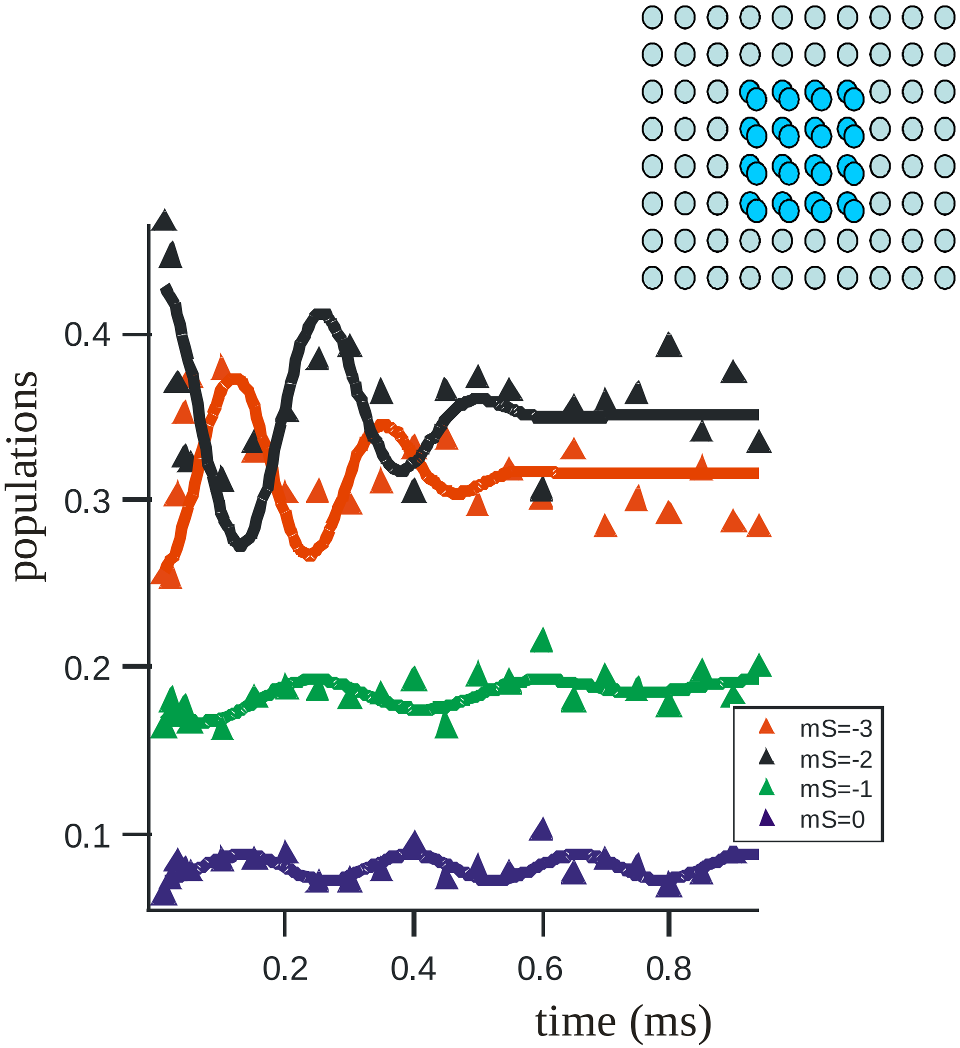
onsite contact interaction:

$$n_0 \; g_S$$



$$g_S = 4\pi \frac{\hbar^2}{m} a_S$$

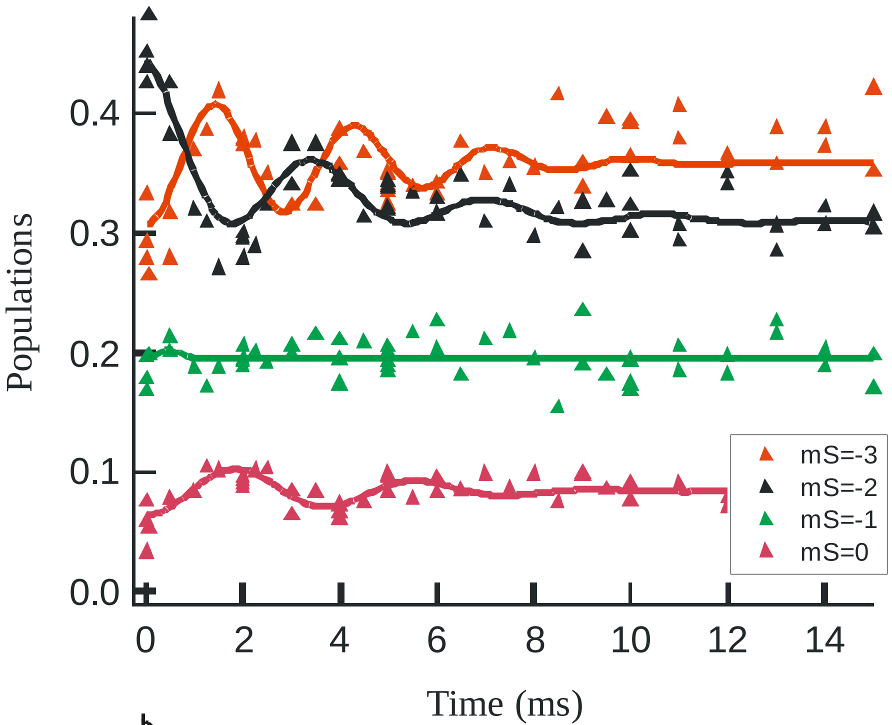
$$T_{contact} = \frac{h}{n_0 (g_6 - g_4)} = 280 \;\; \mu s$$

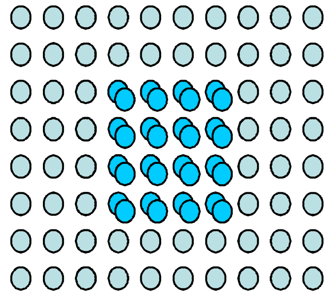


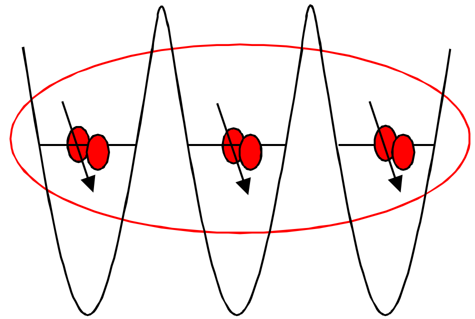
contact spin exchange in 3D lattice:
Bloch PRL 2005, Sengstock Nature Physics 2012

spin oscillations with the expected period
strong damping (rate > 1O J)

Spin exchange dynamics in a 3D lattice with doublons at "long" time scale





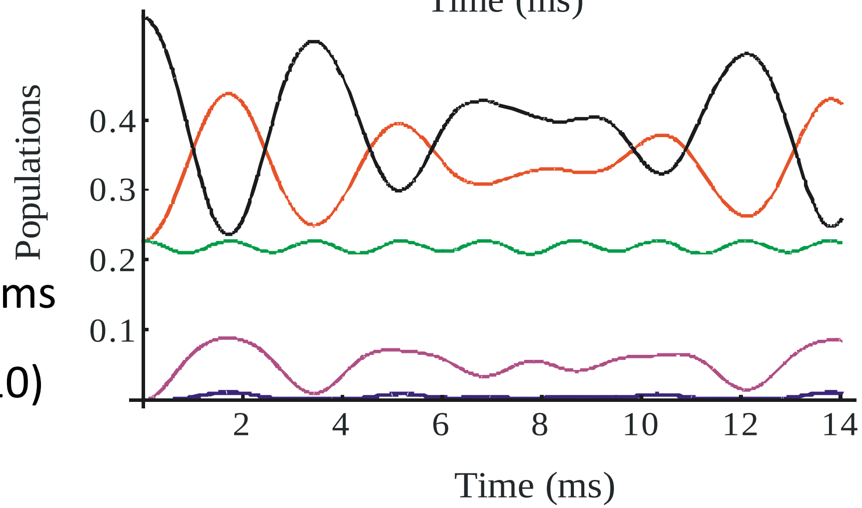


intersite dipolar coupling

result of our toy model:

two sites with two atoms

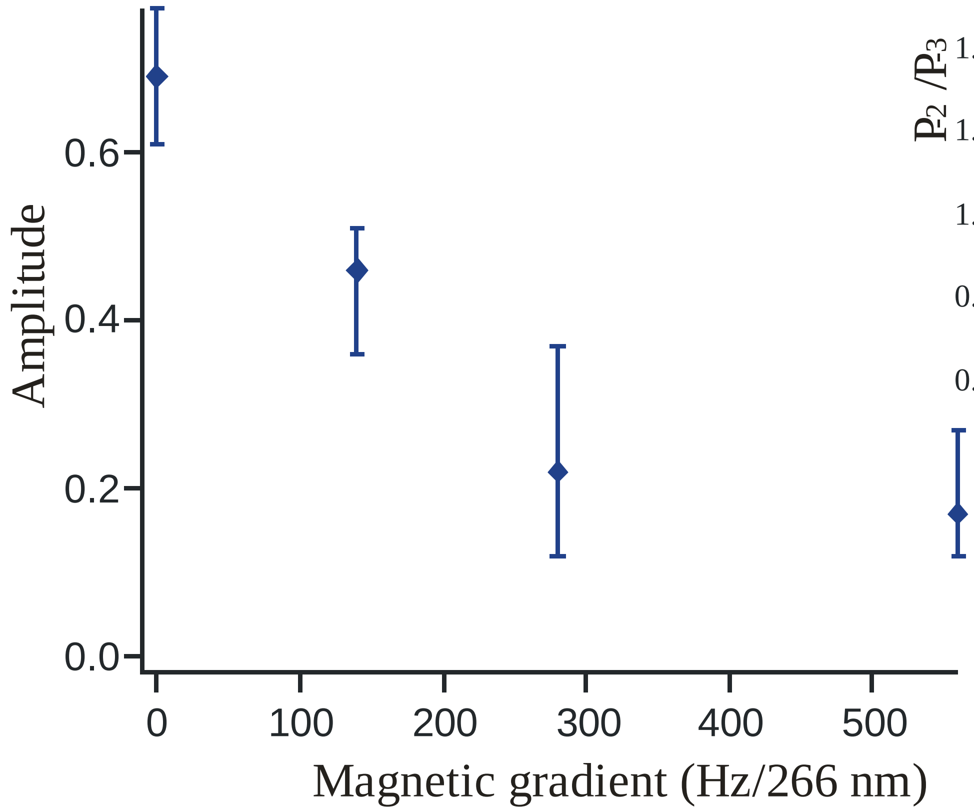
coordination factor (10)

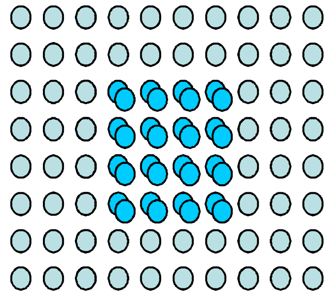


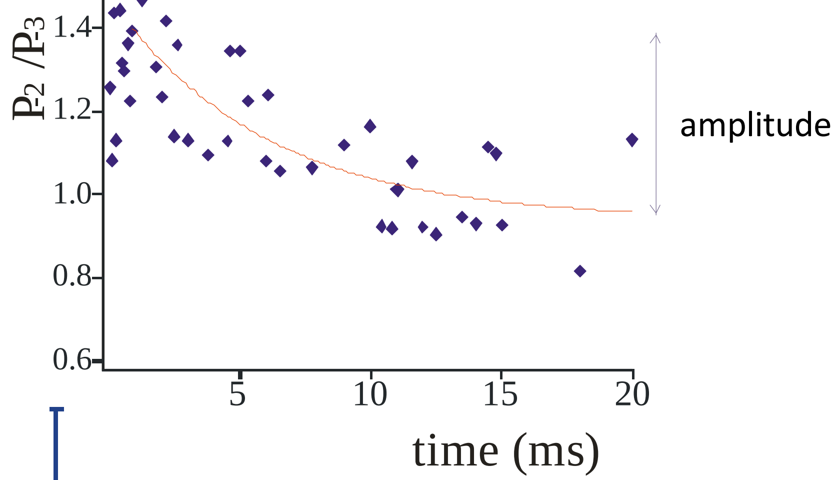
our experiment allows the study of molecular Cr magnets with larger magnetic moments than Cr atoms, without the use of a Feshbach resonance

Spin exchange dynamics in a 3D lattice: strong reduction by a magnetic gradient

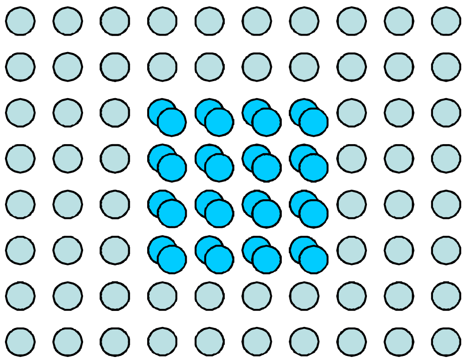
if the spin dynamics results from intersite coupling it should disappear when: $g_S \mu_B \Delta B >$ dipolar coupling rate



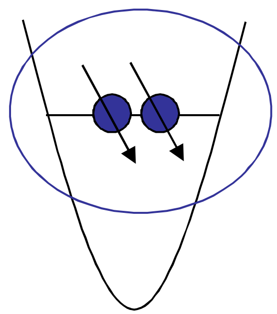




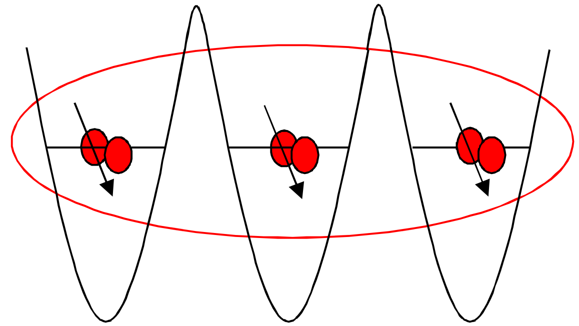
Different Spin exchange dynamics in a 3D lattice



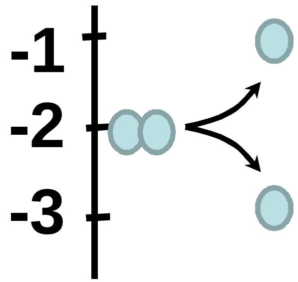
expected Mott distribution

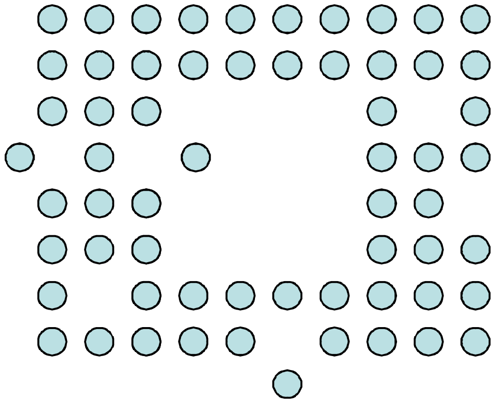


intrasite contact

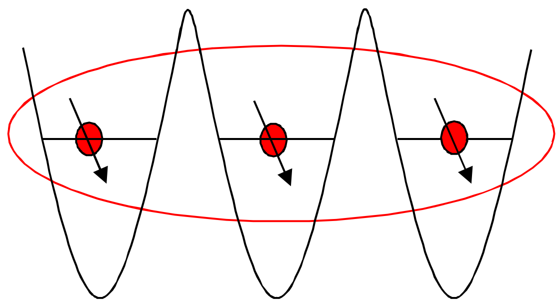


intersite dipolar





doublons removed = only singlons

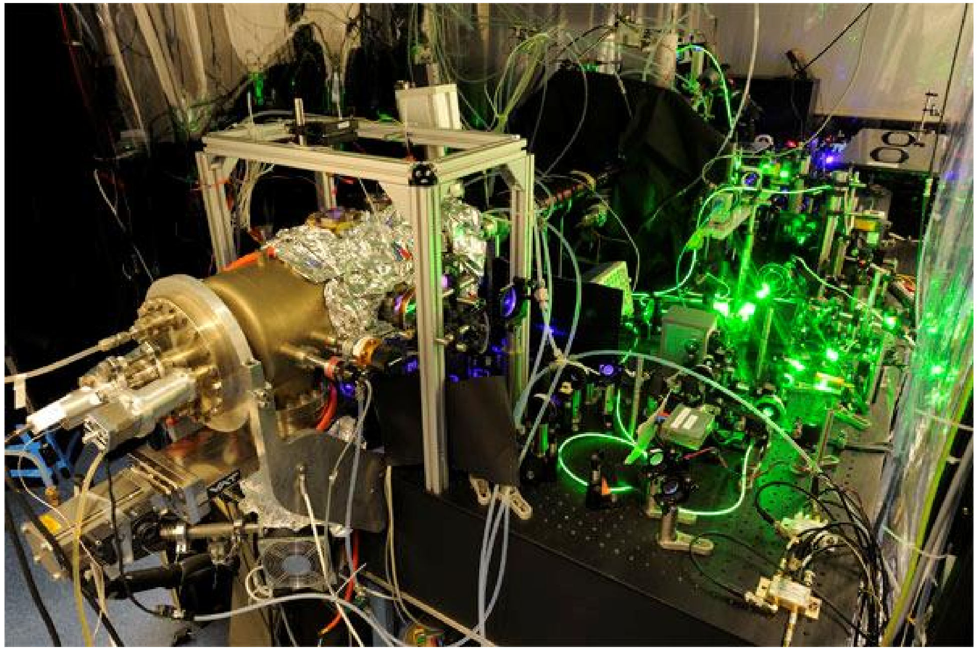


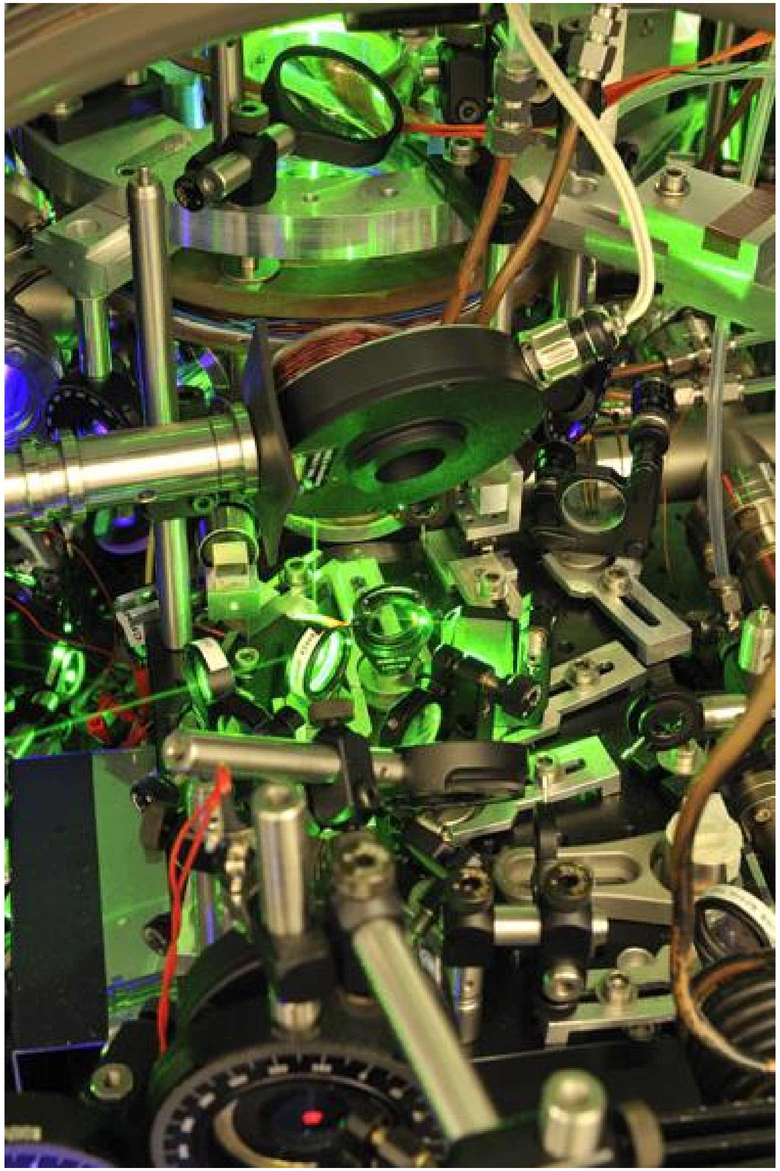
intersite dipolar

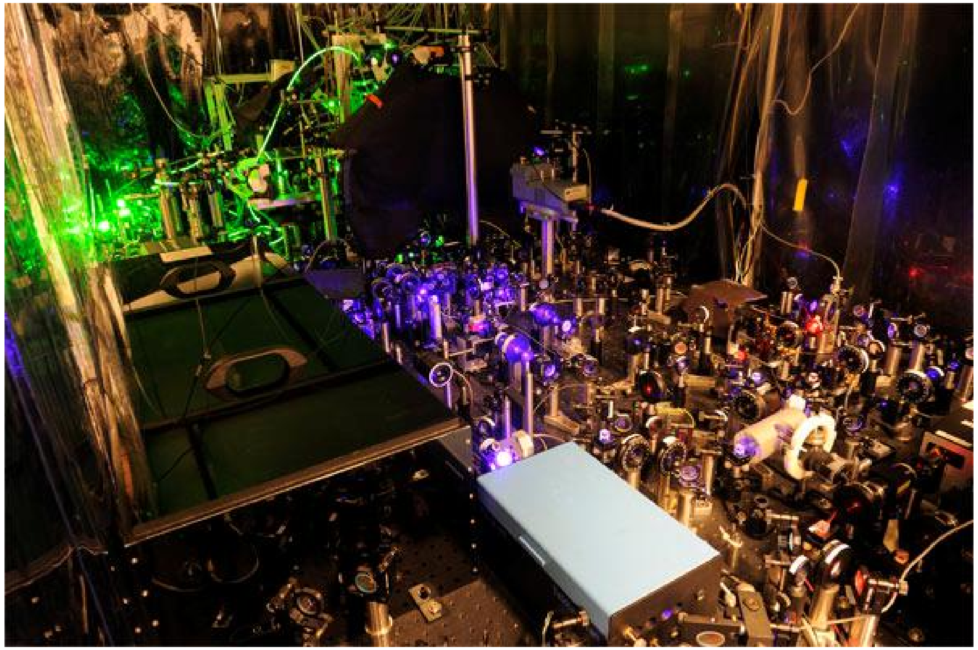
Heisenberg like hamiltonian

$$S_{1z}S_{2z}-\frac{1}{4}\left(S_{1+}S_{2-}+S_{1-}S_{2+}\right)$$

quantum magnetism with S=3 bosons and true dipole-dipole interactions







thank you for your attention!