Large Spin Magnetism

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Chromium dipolar gases - and Strontium project

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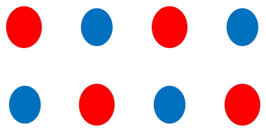
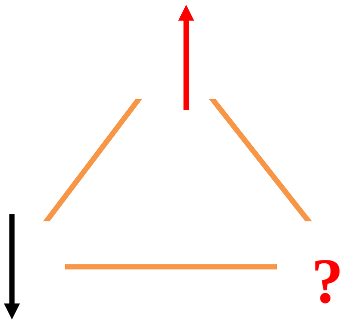
Quantum magnetism, some paradigms from solid-state physics
Strongly correlated (s=1/2) electrons

Condensed matter physics ↔ many-body quantum physics

High-Tc superconductivity ⟷ Antiferromagnetism **Hubbard model**



Frustrated magnetism



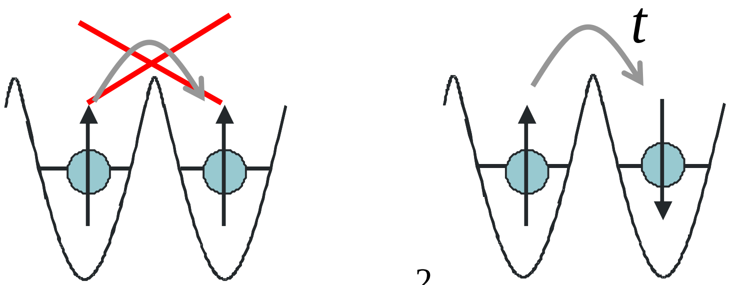
Spin liquids

Heavy fermions (Kondo physics), anomalous superconductivity

Strongly correlated many-body quantum systems: lots of open questions!!

Introduce super-exchange

Condensed-matter: effective spin-spin interactions arise due to exchange interactions



$$\Gamma \propto \frac{t^2}{U}$$

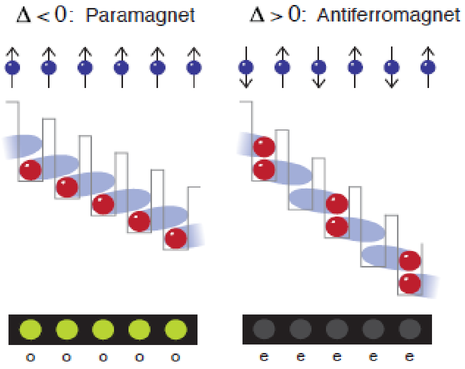
Heisenberg model of magnetism
(real spins, effective spin-spin interaction)

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

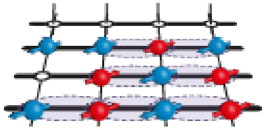
Ising Exchange

Cold atoms offer to revisit paradigms from solid-state physics experimentally.

A “hot” topic : Cold atoms revisit (quantum) magnetism

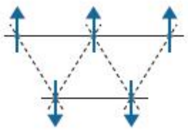


Interacting spin-less bosons
(effective spin encoded in orbital degrees of freedom)
Greiner: **Anti-ferromagnetic (pseudo-)spin chains**
I. Bloch,…



Spin ½ interacting Fermions or Bosons
Super-exchange interaction
Esslinger, Hulet, Bloch, Greiner:
(short range) anti-correlations
T. Porto, W. Ketterle,…

Non-interacting spin-less bosons
Sengstock: **classical frustration**



Ion traps: spin lattice models with effective long-range interactions
C. Monroe

Spinor gases:
Large spin bosons (or fermions)

Stamper-Kurn, Lett, Klempt, Chapman,
Sengstock, Shin, Gerbier, ……

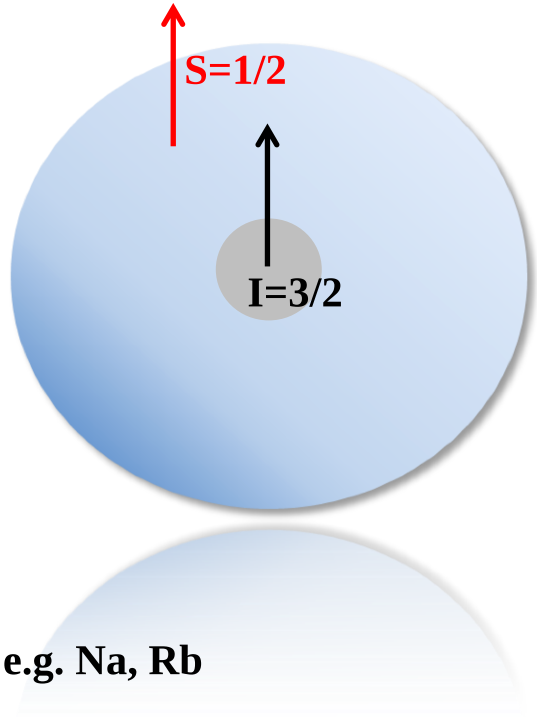
Dipolar gases: long range spin-spin interactions

J. Ye, this work…

Atoms are composite objects, whose spin can be larger than 1/2

$$\vec{F} = \vec{S} + \vec{I}$$

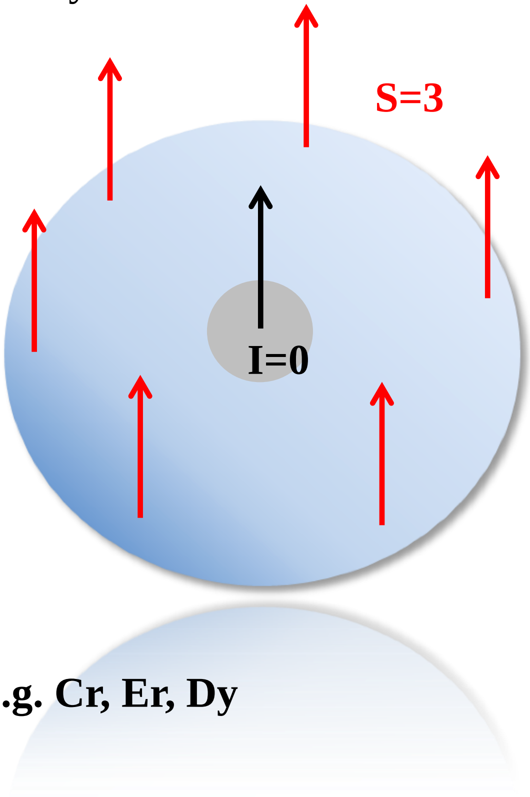
Alkali: spin arrises both from nuclear and electronic spins



e.g. Na, Rb

Spin-dependent
contact interactions

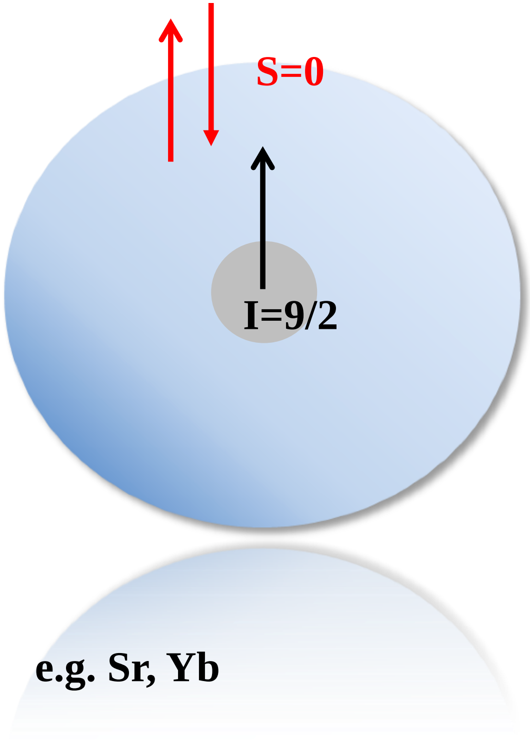
« magnetic atoms »: spin is purely electronic



e.g. Cr, Er, Dy

Strong dipole-dipole
long-range interaction

Alkaline-earth: spin is purely nuclear



e.g. Sr, Yb

Spin-independent
contact interactions

Outline

I **Spinor physics** when spin arrises both from nuclear and electronic spins

The importance of spin-dependent interactions

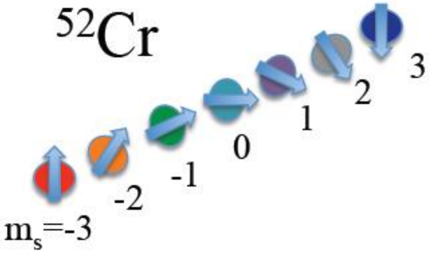
II **Dipolar spinor physics** when the spin is purely electronic

The importance of dipole-dipole interactions

III **SU(N) magnetism** when the spin is purely nuclear

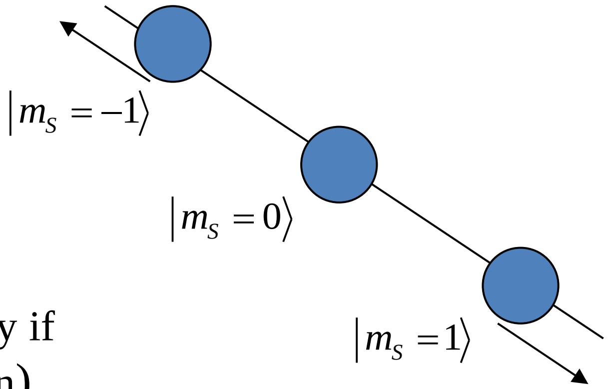
The effects of a new symmetry

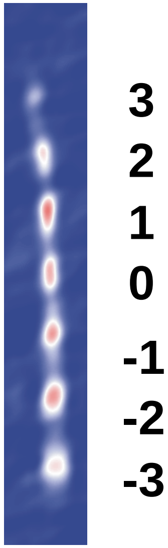
Optical dipole traps equally trap all Zeeman state of a same atom (AC Stark shift)



How to measure?

Stern-Gerlach separation:
(magnetic field gradient)





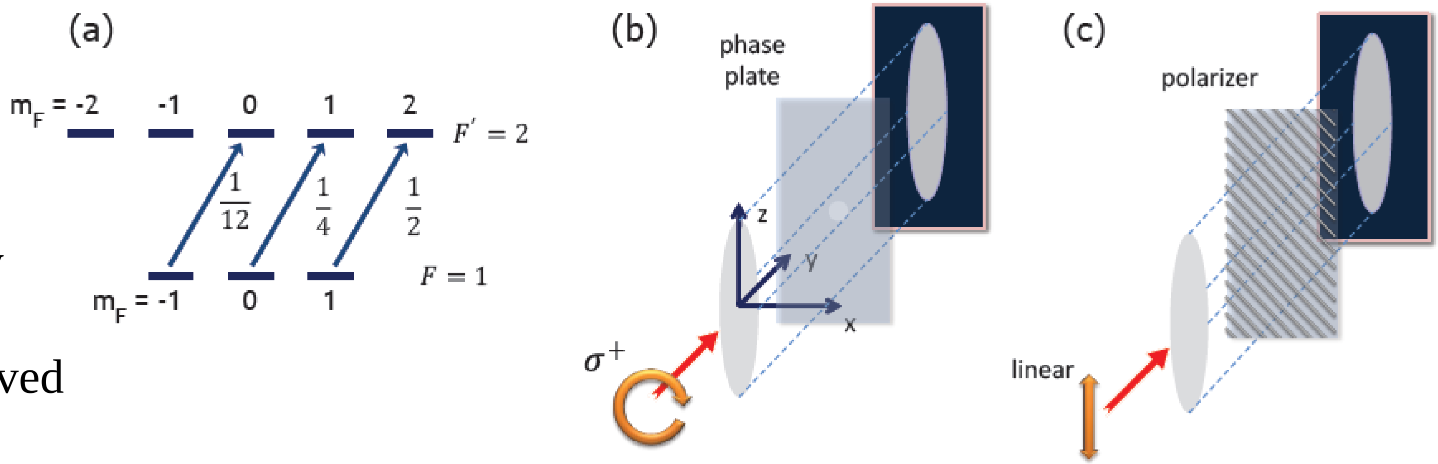
(can be (rather poorly) resolved spatially if separation is fast compared to expansion)
(destructive)

How to better measure?

D. Stamper-Kurn group

Faraday-rotation (-like)

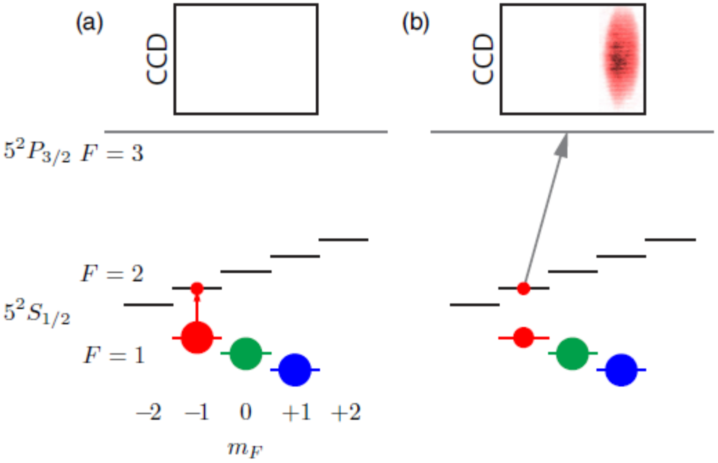
Light propagating through medium is sensitive to its polarization (e.g. through Clebsch Gordan coefficients)



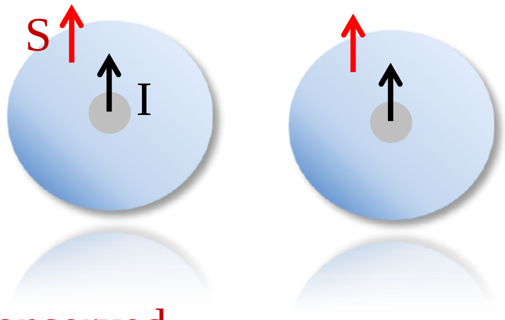
Can be weakly destructive

Spatially resolved

Use the hyperfine structure



How two spin-full atoms collide



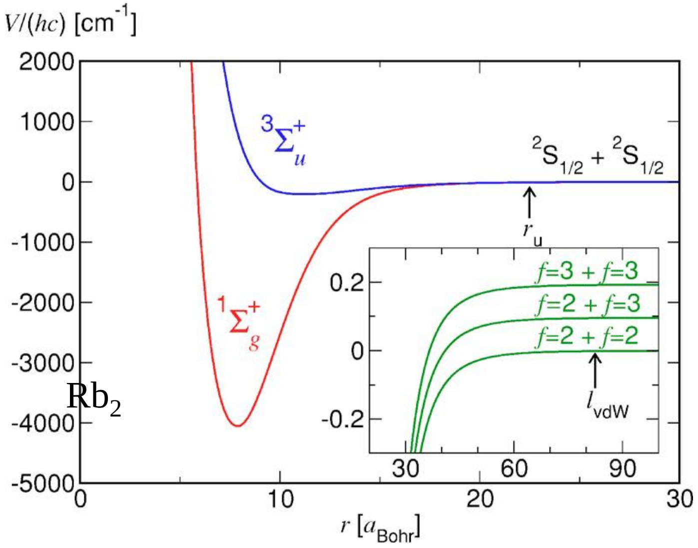
$$\vec{F}_{tot} = \vec{F}_1 + \vec{F}_2 = \vec{S}_1 + \vec{I}_1 + \vec{S}_2 + \vec{I}_2$$

- In absence of anisotropic interaction, total spin F_{tot} is conserved.

- At long range, Van-der-Waals coefficient C_6 independent of F_{tot} (**electrostatic interactions**).

- At short range, interactions strongly depend on electronic spin (**interplay between Coulomb and quantum statistics**).

Therefore scattering length depends on F_{tot} except when S_1=S_2=0



Only even molecular potentials matter

- (Bosons) + (l=0 scattering) → total spin is symmetric → F even

Example: chromium ^{52}Cr S=3 ; S_{tot}=6,4,2,0

- (Fermions) + (l=0 scattering) → total spin is anti-symmetric → F even also !!

Example: potassium ^{40}K F=9/2 ; F_{tot}=8,6,4,2,0

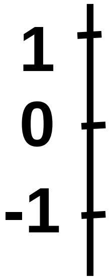
Van-der-Waals (contact) interactions

$$V(R) = -\frac{C_6}{R^6} \longrightarrow V(R) = \frac{4\pi\hbar^2}{m} a_S \delta(R)$$

(whatever F, integer or semi-interger, $F_{tot}=F+F$ is always symmetric)

Example: spin 1 atoms

f=1. Three Zeeman states



Two molecular potentials F=0,2 ; two scattering lengths: a_0, and a_2.

If $a_2 < a_0$: spins align : ferromagnetic

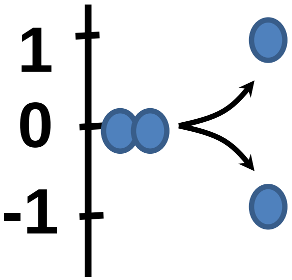
If $a_2 > a_0$: polar phase

Ho 1998 ; Machida 1998

Spinor physics due to contact interactions: scattering length depends on molecular channel

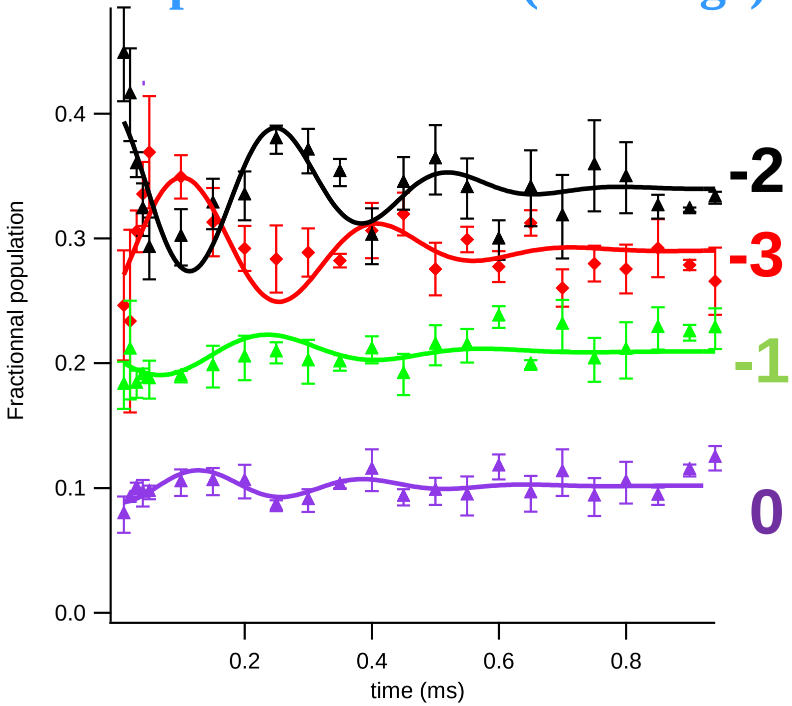
$$\left|s=1, m_s=0; s=1, m_s=0\right\rangle =$$

$$\frac{-1}{\sqrt{3}}\left|S_t=0, m_S=0\right\rangle + \sqrt{\frac{2}{3}}\left|S_t=2, m_S=0\right\rangle$$



$$\boxed{\Gamma = \frac{4\pi\hbar^2}{m}\left(a_2 - a_0\right)n}$$

Spin oscillations (exchange)



Magnetism… at constant magnetization

linear Zeeman effect does not matter

Spin-changing collisions have no analog in spin ½ systems

Spin-exchange interactions, mean-field and beyond

In the case of F=1, spin-exchange interactions are described by

$$\frac{4\pi\hbar^2}{3m}(a_2 - a_0)\int dr\left[\Psi_{-1}^{+}\Psi_{+1}^{+}\Psi_0\Psi_0 + \Psi_0^{+}\Psi_0^{+}\Psi_{-1}\Psi_{+1}\right]$$

Assuming a BEC initially polarized in ms=0, mean-field theory predicts **no spin dynamics!**

$$i\hbar\frac{d\alpha_{+1}}{dt} = \frac{4\pi\hbar^2}{3m}(a_2 - a_0)\alpha_{-1}^{*}\alpha_0\alpha_0 = 0$$

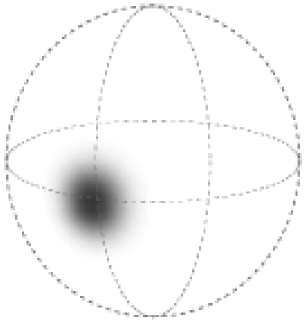
Two-body physics obviously does predics **spin dynamics**

$$\left|F=1, m=0; F=1, m=0\right\rangle = \frac{-1}{\sqrt{3}}\left|F_{tot}=0, m=0\right\rangle + \sqrt{\frac{2}{3}}\left|F_{tot}=2, m=0\right\rangle$$

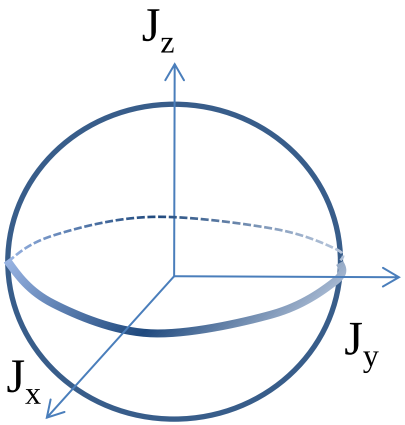
$\left|0,0\right\rangle \leftrightarrow \frac{1}{\sqrt{2}}\left(\left|1,-1\right\rangle + \left|-1,1\right\rangle\right)$ at rate $\Gamma = \frac{4\pi\hbar^2}{m}(a_2 - a_0)n$

Two body collisions introduce correlations which cannot be grasped by mean-field theories!

Spin dynamics and beyond mean-field effects

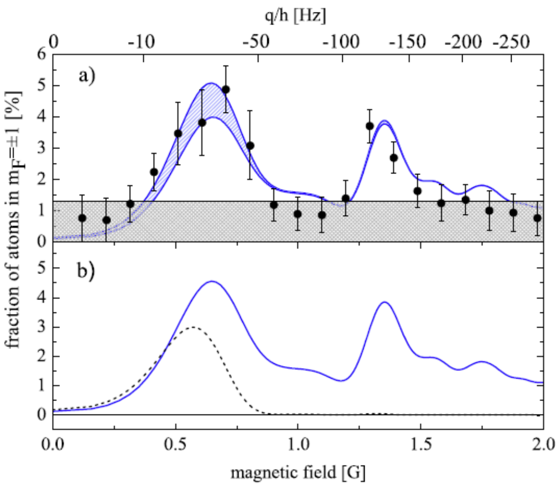


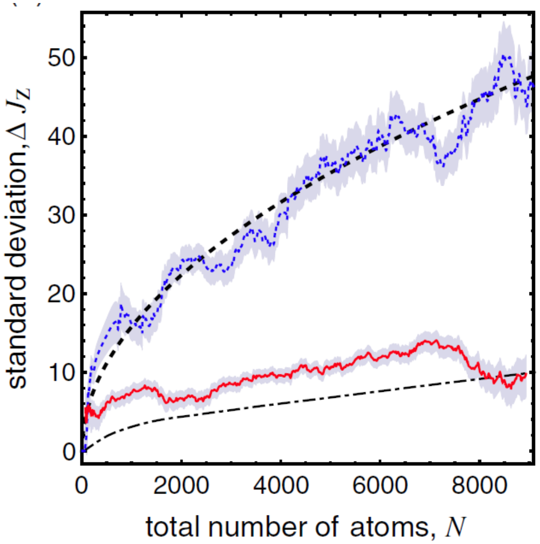
$$|0,0\rangle \leftrightarrow \frac{1}{\sqrt{2}}\left(|1,-1\rangle + |-1,1\rangle\right)$$

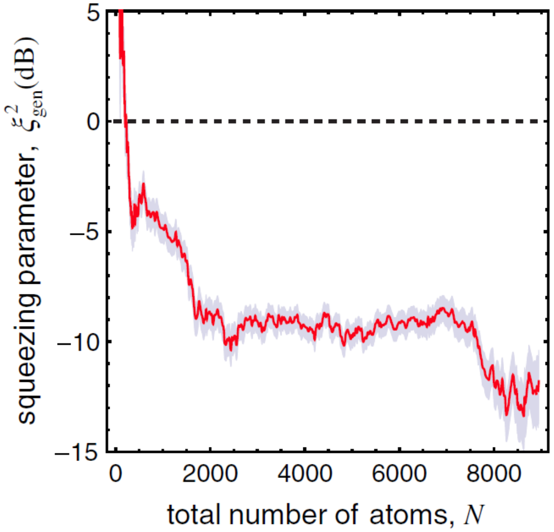


Spin dynamics generates entanglement.

Creates twin beams which may be useful for atom interferometry







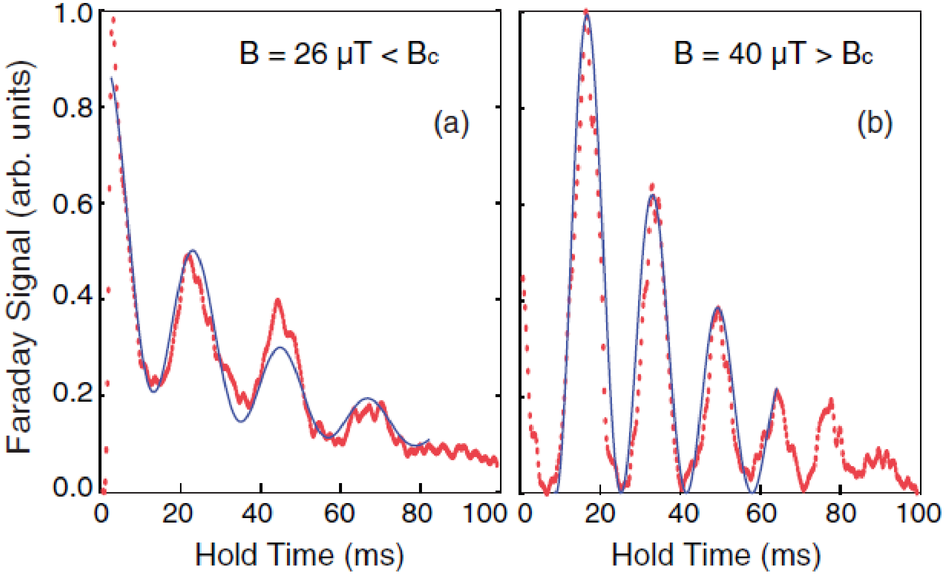
Karsten Klemt, **Hannover: twin beams useful for interferometry ? EPR tests ?**

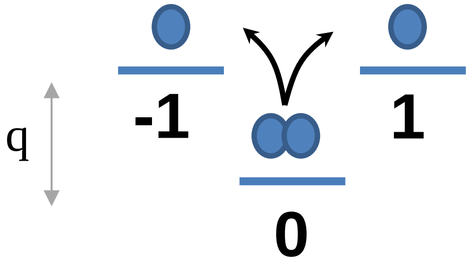
(also M. Chapman)

Effect of the magnetic field

If one only considers spin-exchange interactions, the total longitudinal magnetization is fixed

Therefore linear Zeeman effect is gauged out





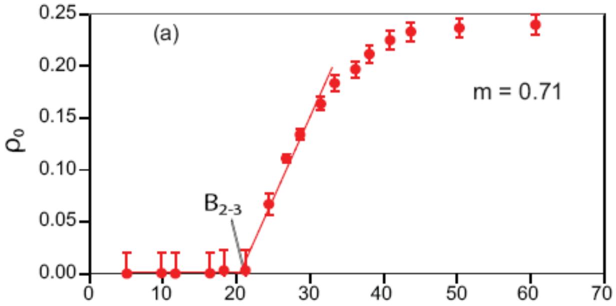
P. Lett

Physics is governed by an interplay between spin-exchange interactions and quadratic Zeeman effect.

Quantum phase transitions

Quantum phase transitions

(interplay between spin-dependent contact interactions and Quadratic Zeeman effect)

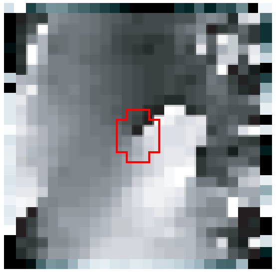


Stamper-Kurn,
Lett,
Gerbier

New Nematic phases (the spin does not point a well-defined position)

Quench through phase transitions

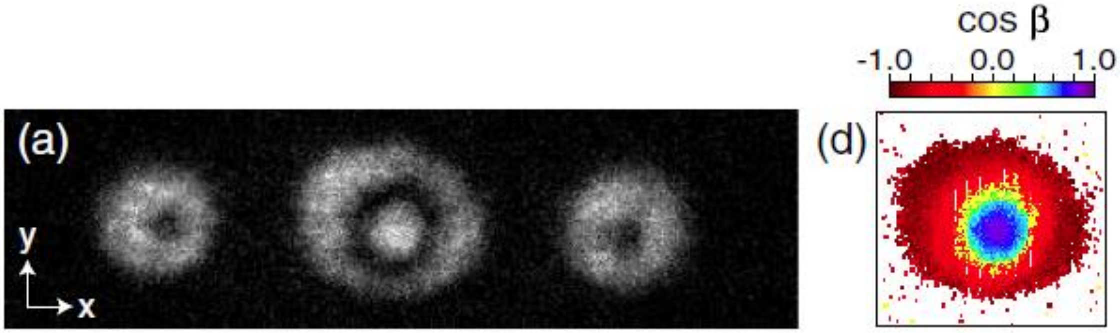
Here, generation of topological defects



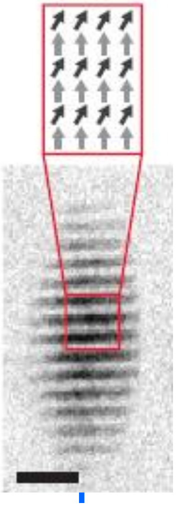
Stamper-Kurn

Domains, spin textures, spin waves, topological states

Stamper-Kurn, Chapman,
Sengstock, Shin…



Skyrmions, Shin…



Yet to come…

The Bragg spectrocopy of (mixed-) spin and density excitations is still very poorly explored experimentally

Many new excitations, get increasingly interesting (e.g. non abelian) for increasing spin.

Effects on BEC/superfluid transition ?

Towards « non-classical » spinor phases ?
What is the true nature of the ground state

$$|SC\rangle = \frac{1}{\sqrt{N!}}\left(\sqrt{\frac{N_1}{N}}a_1^\dagger + e^{i\chi}\sqrt{\frac{N_{-1}}{N}}a_{-1}^\dagger\right)^N |\mathrm{vac}\rangle$$

a2>a0: Possibility of singlet condensates

$$\boxed{\Theta^+ = -2a_1^+ a_{-1}^+ + a_0^{+\,2}}$$

Creates a pair

$$\boxed{|PC\rangle = \left(\Theta^+\right)^{N/2}|vac\rangle}$$

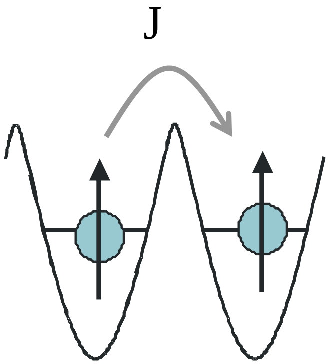
Pair condensate is the real ground state !

a2<a0: Ferromagnetic; Spontaneous symmetry breaking

See Bigelow 1998 ; Ho 2000

Yet to come: spinor gases in lattices

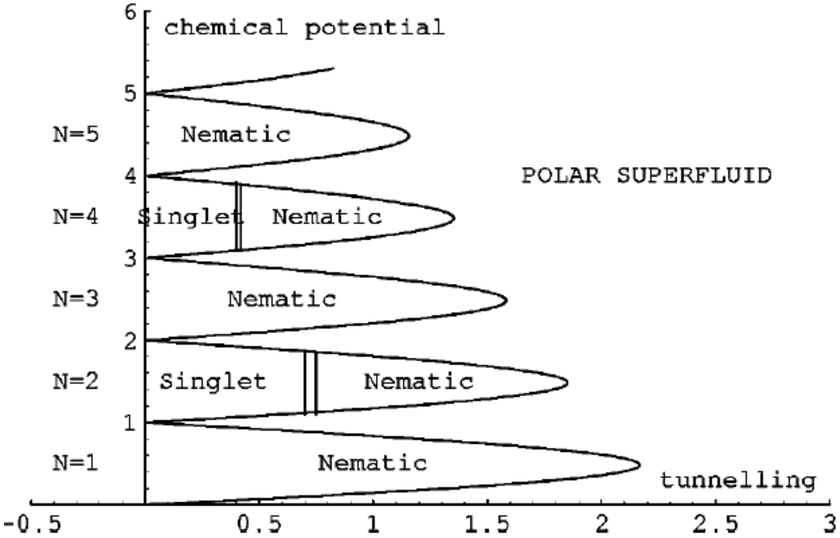
Start with two bosons in two sites (insulating states) ; allow perturbatively for tunneling



$$H = -J_1 \vec{S}_1 . \vec{S}_2 - J_2 (\vec{S}_1 . \vec{S}_2)^2$$

$$J_i \propto J^2 / U$$

S_{tot}	$\vec{S}_1 \cdot \vec{S}_2$	$(\vec{S}_1 \cdot \vec{S}_2)^2$	Energy
0	-2	4	$2J_1 - 4J_2$
1	-1	1	$J_1 - J_2$
2	1	1	$-J_1 - J_2$



J_1 favors $S_{tot}=2$
J_2 favors $S_{tot}=0$

$J_2 > J_1$ →singlet

In a lattice, cannot have singlet at each bond →nematic

Demler PRA (2003)

Outline

I Spinor physics when spin arrises both from nuclear and electronic spins

The importance of spin-dependent interactions

II **Dipolar spinor physics** when the spin is purely electronic

The importance of dipole-dipole interactions

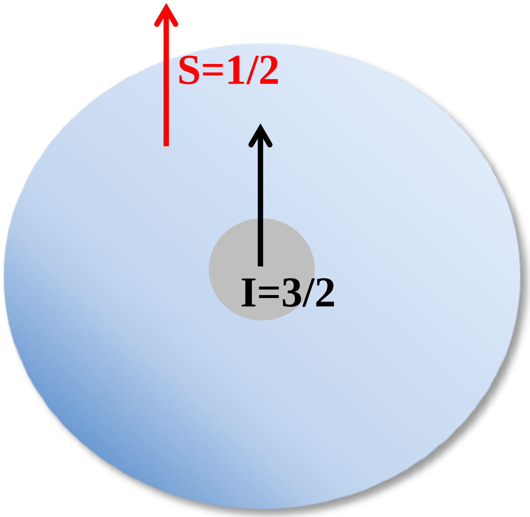
III **SU(N) magnetism** when the spin is purely nuclear

The effects of a new symmetry

Atoms are composite objects, whose spin can be larger than 1/2

$$\vec{F} = \vec{S} + \vec{I}$$

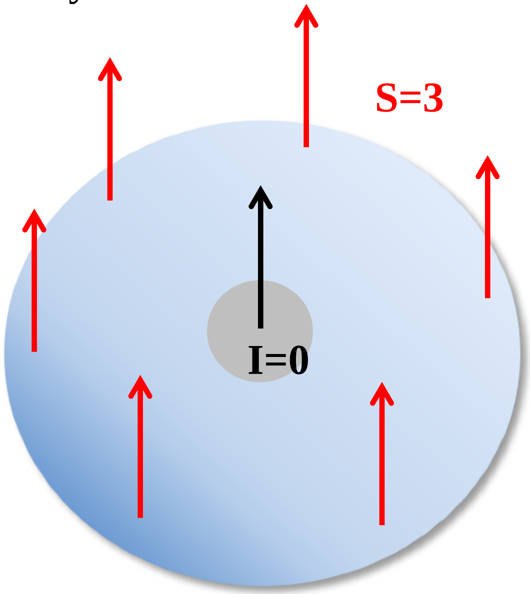
Alkali: spin arrises both from nuclear and electronic spins



e.g. Na, Rb

Spin-dependent
contact interactions

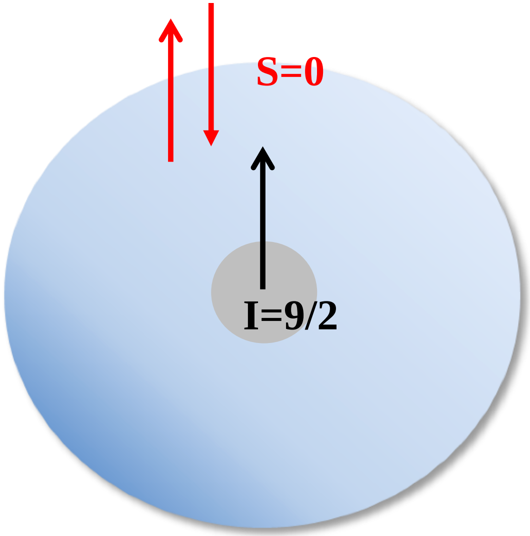
« magnetic atoms »: spin is purely electronic



e.g. Cr, Er, Dy

Strong dipole-dipole
long-range interaction

Alkaline-earth: spin is purely nuclear



e.g. Sr, Yb

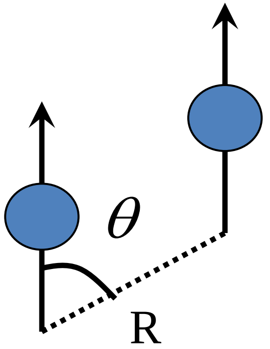
Spin-independent
contact interactions

Magnetic atoms: unusually large dipolar interactions

(large electronic spin)

Dipole-dipole interactions

$$V_{dd} = \frac{\mu_0}{4\pi} S^2 \left(g_J \mu_B\right)^2 \left(1 - 3\cos^2(\theta)\right) \frac{1}{R^3}$$



Long range

Anisotropic

Van-der-Waals (contact) interactions

$$V(R) = -\frac{C_6}{R^6} \longrightarrow V(R) = \frac{4\pi\hbar^2}{m} a_S \delta(R)$$

Short range

Isotropic

(only few experiments worldwide with non-negligible dipolar interactions
- Stuttgart, Paris, Innsbruck, Stanford, Boulder, Boston, Hong-Kong,…)

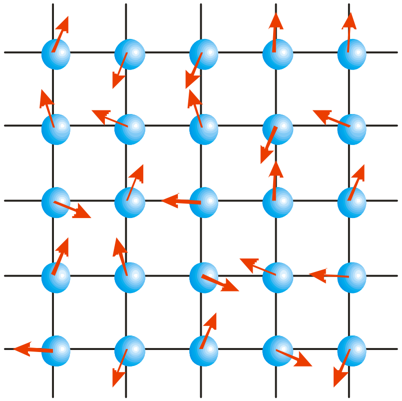
S≥3 **S=1/2**

Two new features introduced by dipolar interactions:

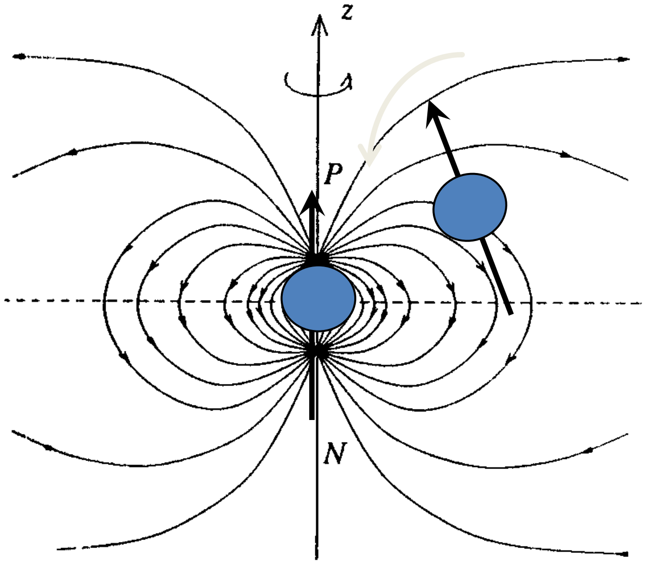
Non-local coupling between spins

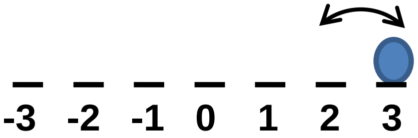
$$V_{dd} \propto \frac{1}{R^3}$$

Implications for lattice magnetism



Free Magnetization

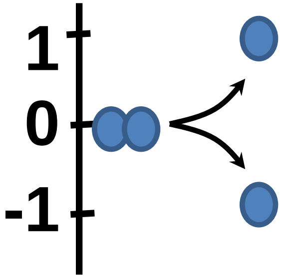




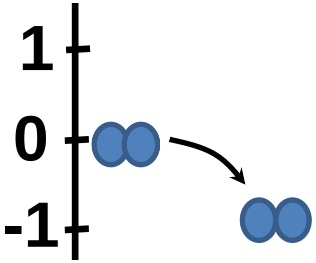
$$\hbar\Gamma \approx V_{dd}$$

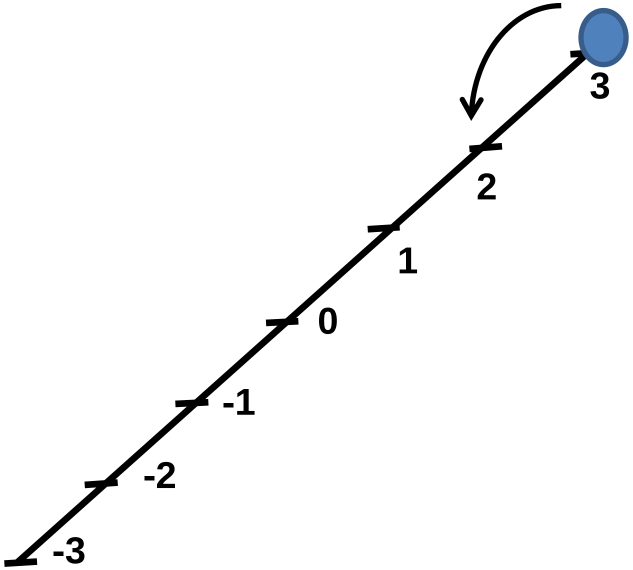
Spinor physics with free magnetization

Without
dipolar
interactions



With
anisotropic
V_{dd}





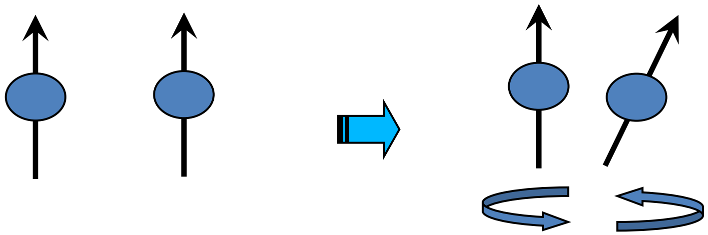
B=1G
→ Particle leaves the trap

B=10 mG
→ Energy gain matches band
excitation in a lattice

B=.1 mG
→ Energy gain equals to
chemical potential in BEC

Magnetic field matters !

Free magnetization and spin-orbit coupling



Spin-orbit coupling
(conservation of total angular
momentum)

Rotate BEC ?
Vortex ?
Einstein-de-Haas effect
Quantum Hall regime with fermions?

$$\Delta E = \Delta m_S g \mu_B B$$

Ueda, PRL **96**, 080405 (2006)
Santos PRL **96**, 190404 (2006)
Gajda, PRL **99**, 130401 (2007)
B. Sun and L. You, PRL **99**, 150402 (2007)
Buchler, PRL **110**, 145303 (2013)

Lattice
Magnetization changing
processes write an x+iy
intersite phase

Flat bands, topological insulators
XYZ magnetism
Frustration

Carr, New J. Phys. **17** 025001 (2015)
Peter Zoller PRL **114**, 173002 (2015).
H.P. Buchler, Phys. Rev. A **91**, 053617 (2015).
Ana Maria Rey, Nature Comm. **5**, 5391 (2014).

engineer $\Delta E = 0$

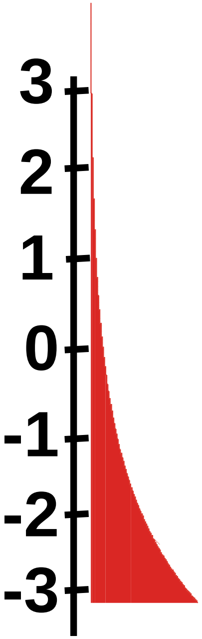
Spin temperature equilibriates with mechanical degrees of freedom

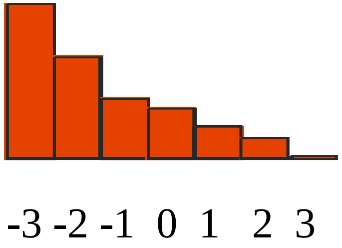
(due to magnetization changing collisions)

At low magnetic field: spin thermally activated

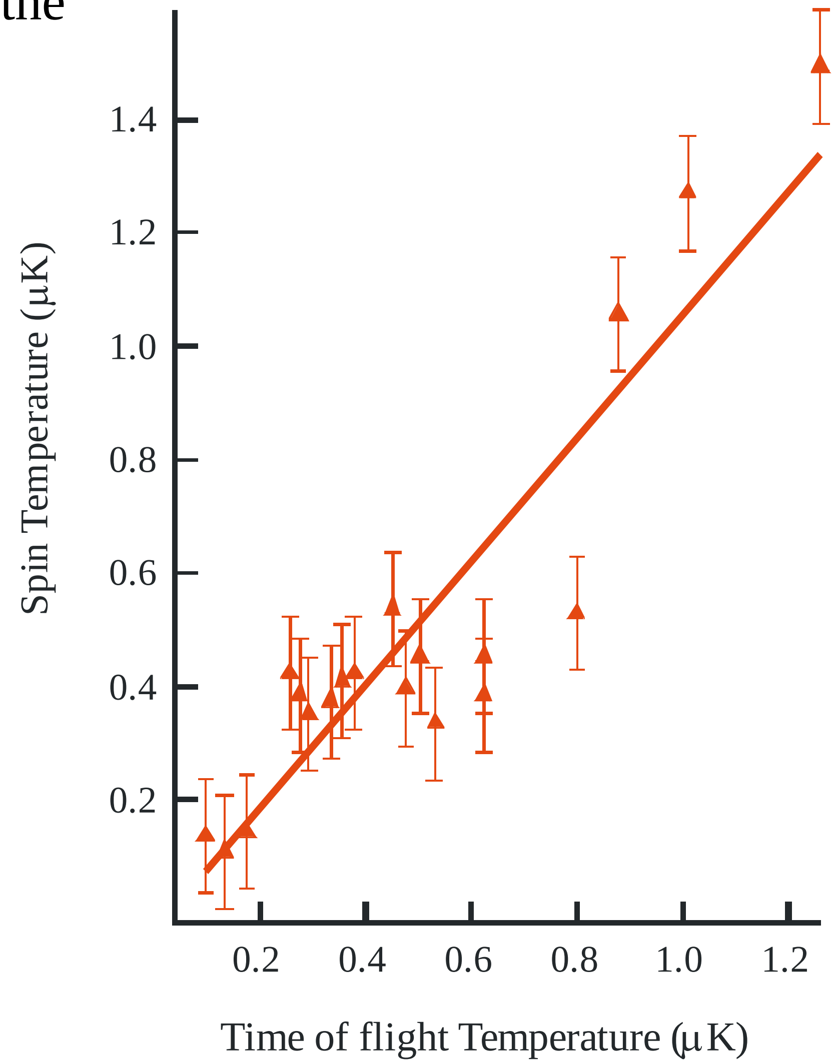
Magnetization adpats to temperature due to the presence of dipolar interactions

$$g\mu_B B \approx k_B T$$



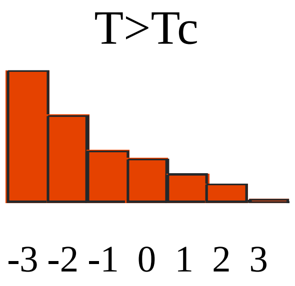


We measure spin-temperature by fitting the m_S population (separated by Stern-Gerlach technique)

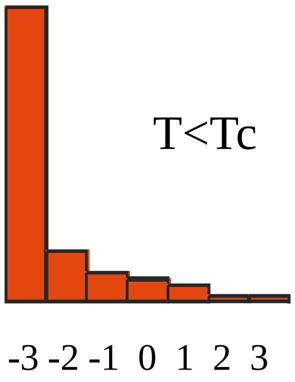


Related to Demagnetization Cooling expts,
T. Pfau, *Nature Physics* **2**, *765 (2006)*

The BEC always forms in the m_s=-3

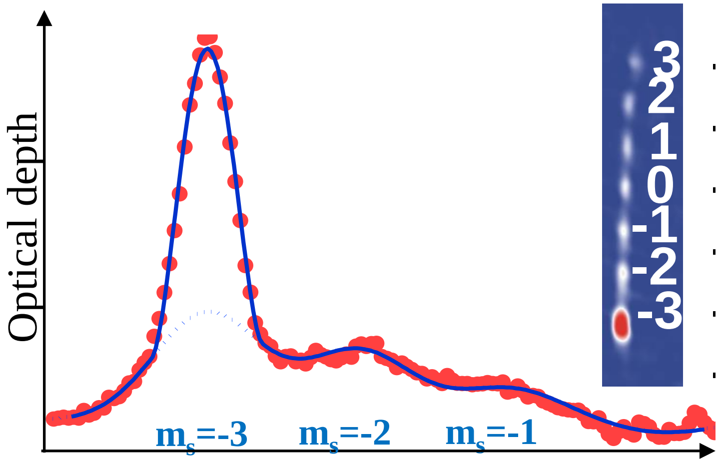


Thermal population in Zeeman excited states



a bi-modal spin distribution

BEC only in m_S=-3 (lowest energy state)

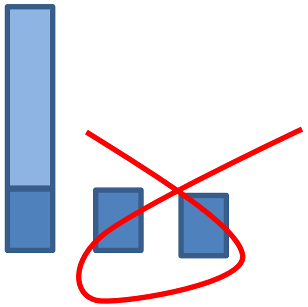


Momentum distribution in the different Zeeman states

PRL **108**, 045307 (2012)

One idea: Kill spin-excited states ?

Provides a loss specific for thermal fraction



Should lead to purification of the BEC, thus cooling

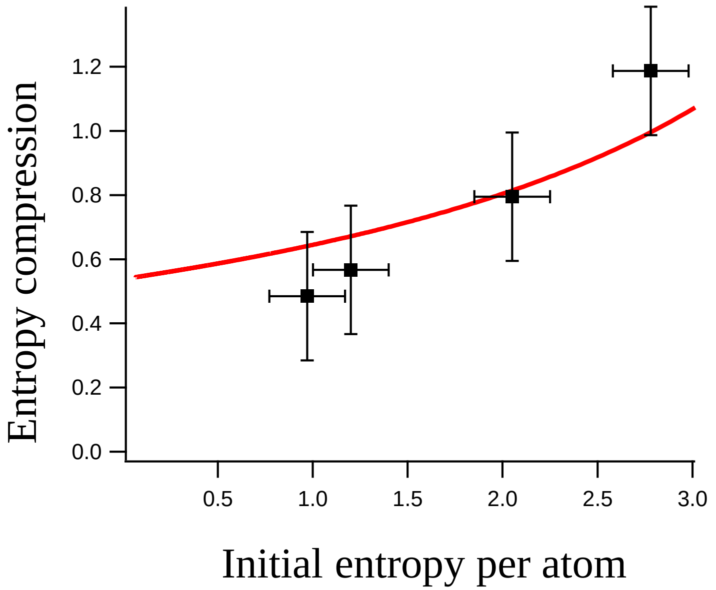
(and this process can be repeated after waiting for more depolarization)

Cooling efficiency

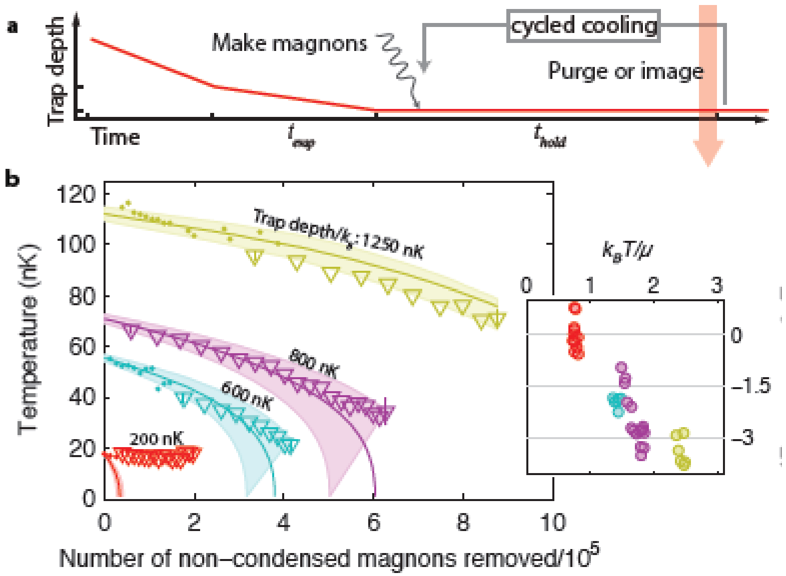
All the entropy lies in the thermal cloud

Thus spin filtering is extremely efficient!

In principle, cooling efficiency has no limitation



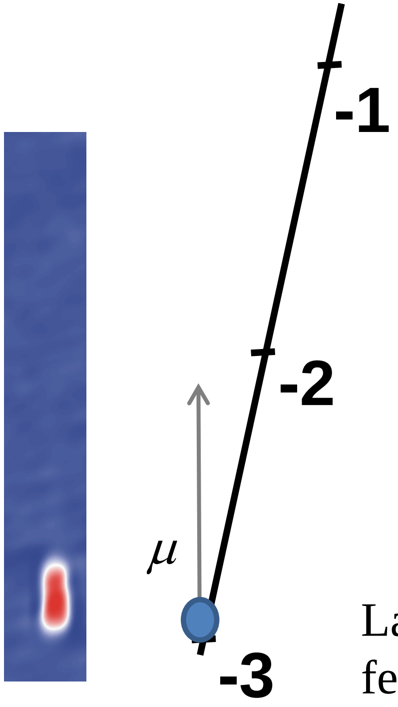
Chromium, LPL, Phys. Rev Lett. (2015)



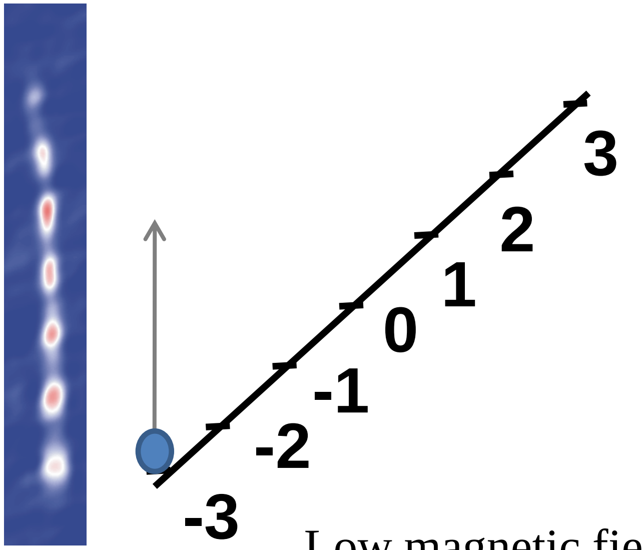
Rb, Stamper Kurn, Nature Physics (2015)

Use spin to store and remove entropy

New magnetic phases at low field

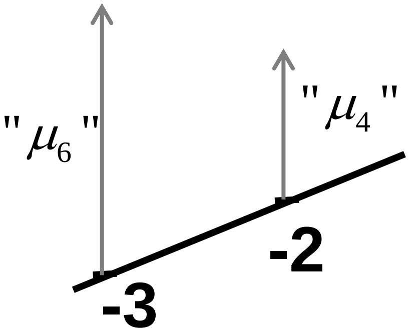


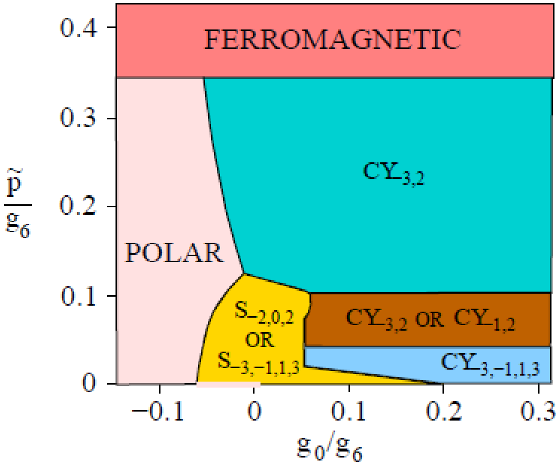
Large magnetic field :
ferromagnetic



Low magnetic field :
polar/cyclic

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





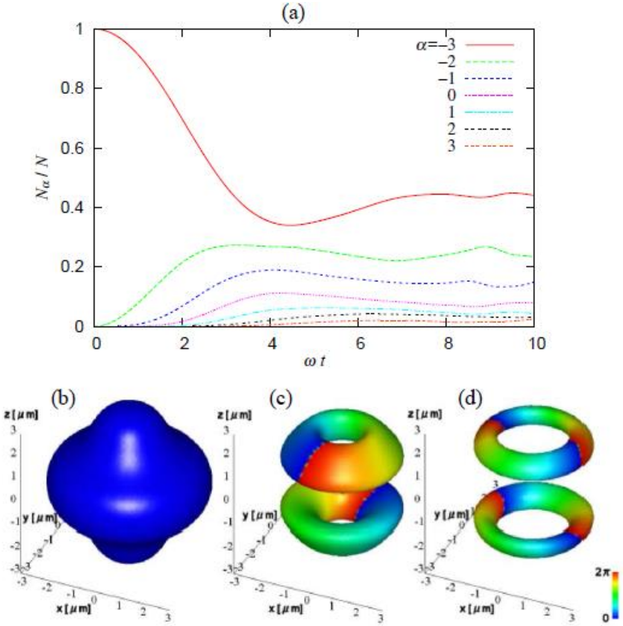
Santos PRL **96**,
190404 (2006)

Ho PRL. **96**,
190405 (2006)

Depolarization observed (Phys. Rev. Lett. **106**, 255303 (2011) ; phases remain to be studied

Two interesting proposals:

Einstein-de Haas effect



Santos PRL **96**,
190404 (2006)

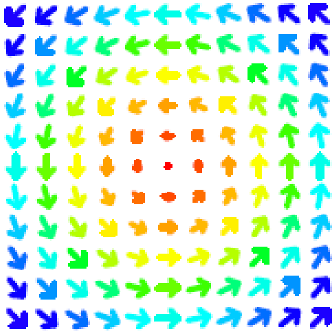
Ho PRL. **96**,
190405 (2006)

Spontaneous circulation in the ground state

$$\tilde{V}_{dd} \propto \int d^3\vec{k}\left[3\left|\vec{F}(\vec{k}).\vec{k}/k\right|^2 - \left|\vec{F}(\vec{k})\right|^2\right]$$

$\vec{F}(\vec{k})$ Fourier transform of magnetization vector

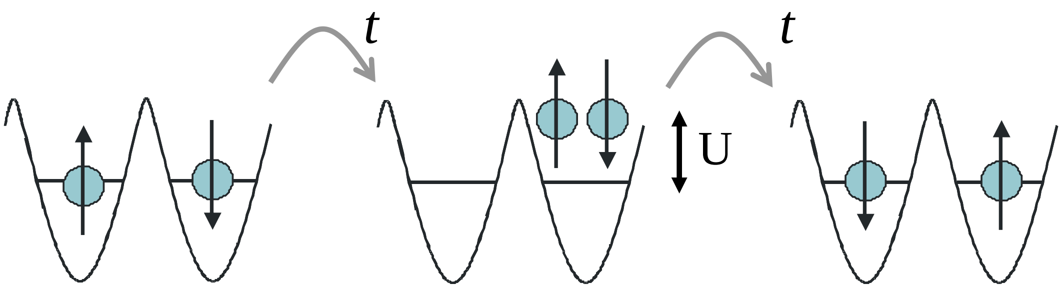
Maximize $\left|\vec{F}(\vec{k})\right|$ and $\vec{F} \perp \vec{k}$



Ueda PRL **97**, 130404 (2006)
S. Yi and H. Pu,
PRL **97**, 020401 (2006)

Study quantum magnetism with dipolar gases ?

Condensed-matter: effective spin-spin interactions arise due to exchange interactions



$$\Gamma \propto \frac{t^2}{U}$$

(Super-) Exchange (I)

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

Ising Exchange

Heisenberg model of magnetism

(real spins s=1/2, effective spin-spin interaction)

Dipole-dipole interactions between real spins

$$V_{dd} = \frac{\mu_0}{4\pi}\left(g_J\mu_B\right)^2 \frac{S_1.S_2 - 3(S_1.\vec{u}_R)(S_2.\vec{u}_R)}{R^3}$$

$$\boxed{\begin{array}{l} S_{1z}S_{2z} + \frac{1}{2}\left(S_{1+}S_{2-} + S_{1-}S_{2+}\right) \\ -\frac{3}{4}\left(2zS_{1z} + r_-S_{1+} + r_+S_{1-}\right). \\ \left(2zS_{2z} + r_-S_{2+} + r_+S_{2-}\right) \end{array}}$$

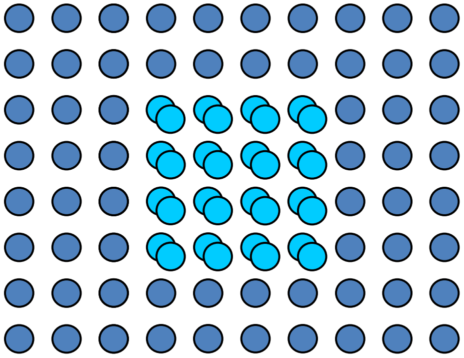
Magnetization changing collisions

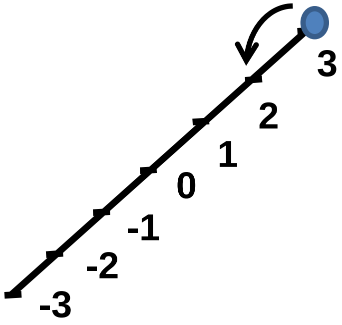
$$S_1^- S_2^-$$

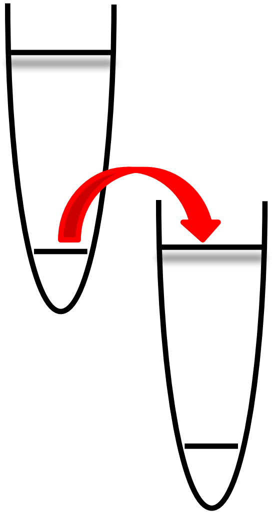
Control of magnetization-changing collisions:
Magnetization dynamics resonance for a Mott state with two atoms per site (~15 mG)

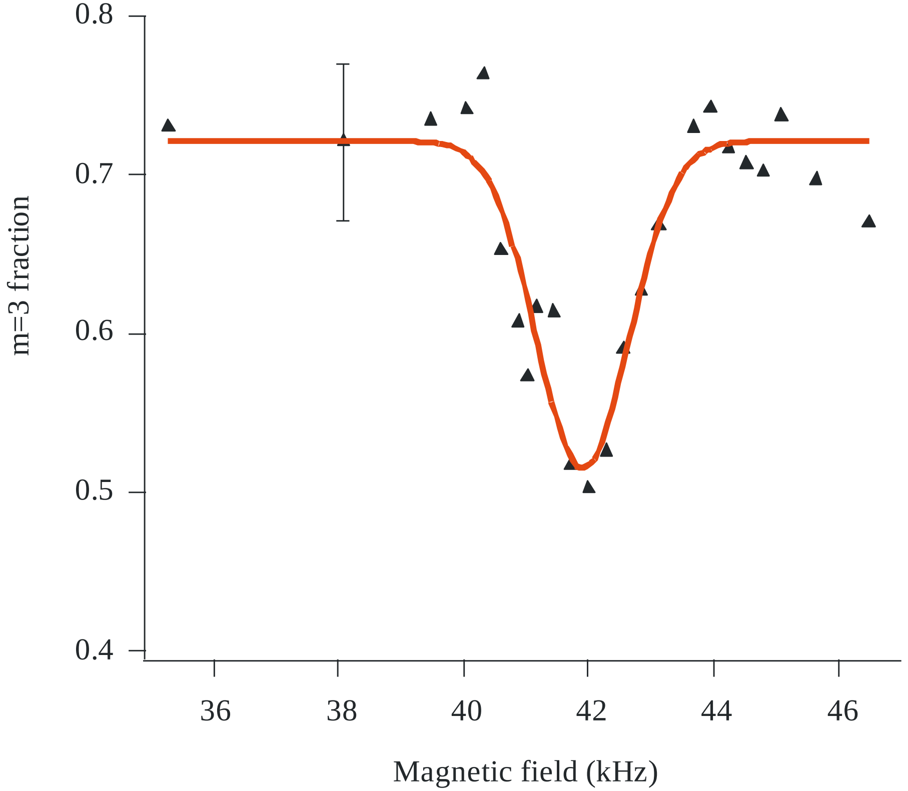
Magnetization changing collisions

$S_1^- S_2^-$









Dipolar resonance when released energy matches band excitation

Phys. Rev. A **87**, 051609 (2013)

See also Gajda: Phys. Rev. A **88**, 013608 (2013)

From now on : stay away from dipolar magnetization dynamics resonances,

Spin dynamics at constant magnetization (<15mG)

Magnetization
changing collisions
Can be suppressed in
optical lattices

$$\xcancel{S_1^- S_2^-}$$

$$\boxed{\left(S_{1z}.S_{2z} - \frac{1}{4}\left(S_{1+}S_{2-} + S_{1-}S_{2+}\right)\right)\left(1-3z^2\right)}$$

Dipolar exchange (II)

NMR-like secular Hamiltonian ressembles but differs from Heisenberg magnetism:

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

Related research with polar molecules:

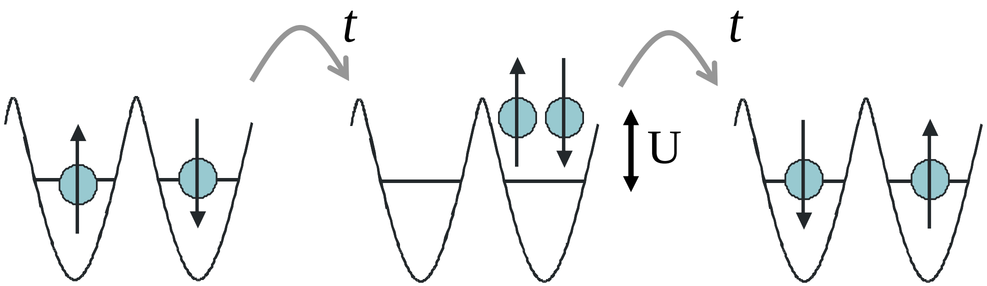
A. Micheli et al., Nature Phys. **2**, 341 (2006).
A.V. Gorshkov et al., PRL, **107**, 115301 (2011),
See also D. Peter et al., PRL. **109**, 025303 (2012)

$$\boxed{\alpha S_{1z}S_{2z} + \beta\frac{1}{2}\left(S_{1+}S_{2-} + S_{1-}S_{2+}\right)}$$

See Jin/Ye group Nature (2013)

Exotic quantum magnetism of large spin, from Mott to superfluid

An exotic magnetism driven by the competition between three types of exchange



$$\Gamma \propto \frac{t^2}{U}$$

Super- Exchange (I)

(nearest neighbor)

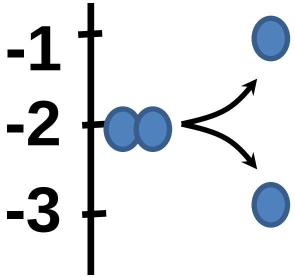
decreases with lattice depth

$$\left(S_{1z}.S_{2z} - \frac{1}{4}\left(S_{1+}S_{2-} + S_{1-}S_{2+}\right)\right)\frac{\left(1-3z^2\right)}{r^3}$$

Dipolar exchange (II)

(true long range)

independent from lattice depth

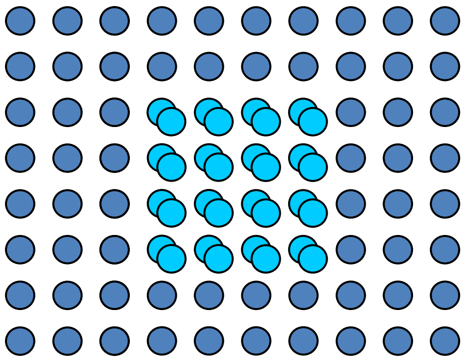


$$\Gamma = \frac{4\pi\hbar^2}{m} n\left(a_6 - a_4\right)$$

Contact exchange (III)

(short range)

Increases with lattice depth

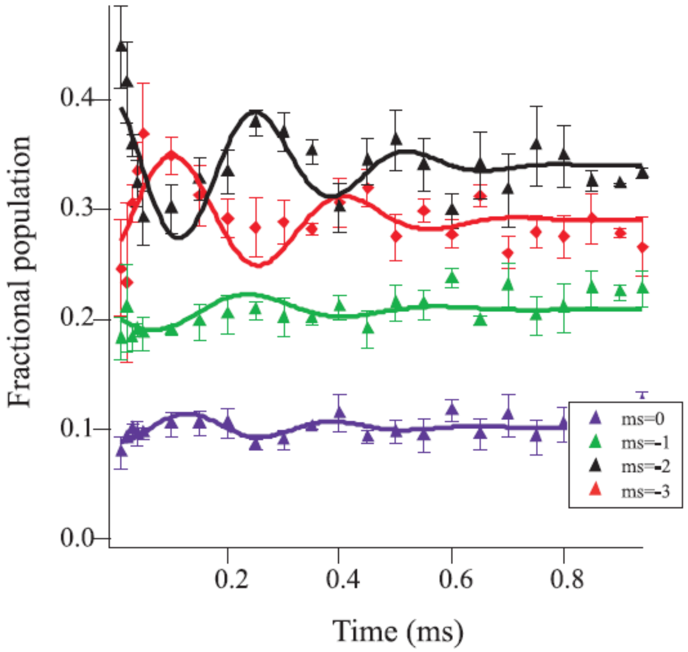


1- At large lattice depths (Mott regime)

In presence of doubly-occupied sites:

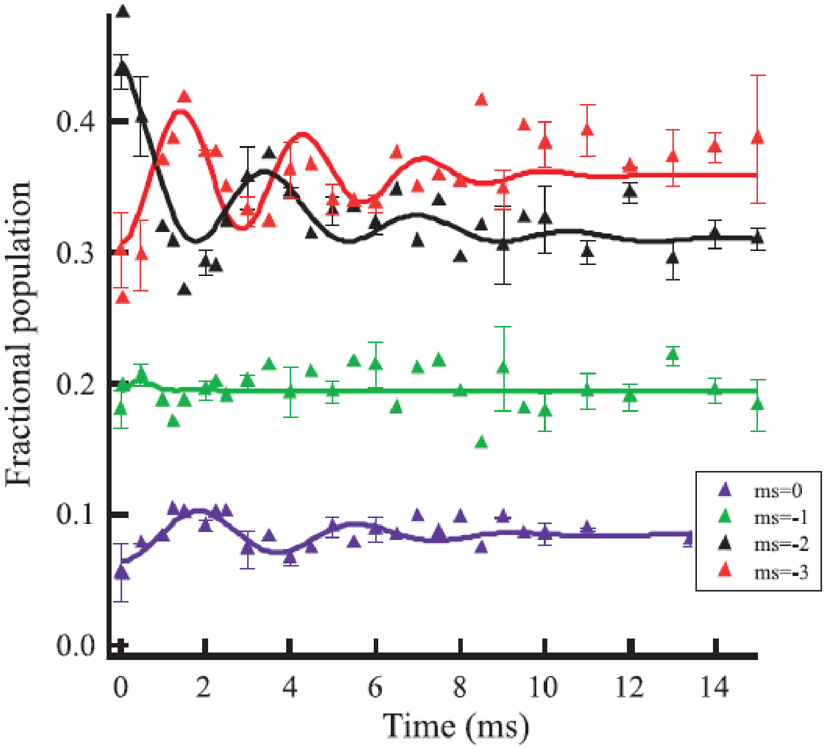
A complex oscillatory behavior dispplaying two distinc frequencies

Phys. Rev. Lett., 111, 185305 (2013)



Contact exchange (III)

$$\Gamma = \frac{4\pi\hbar^2}{m} n\left(a_6 - a_4\right)$$



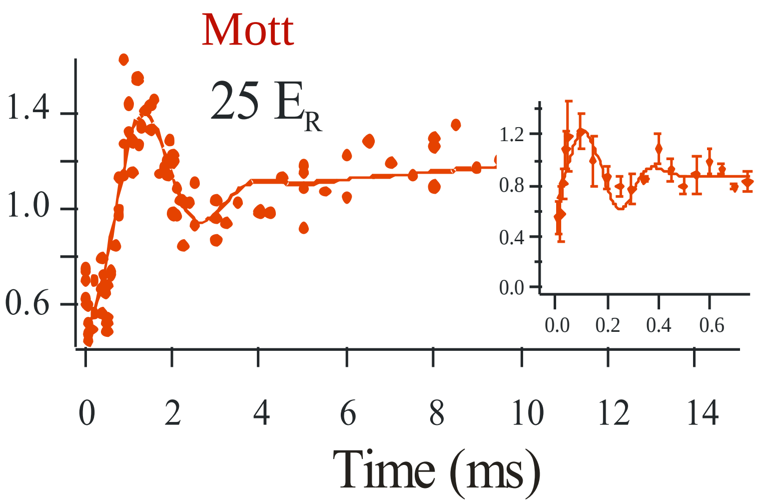
Dipolar Exchange (II)

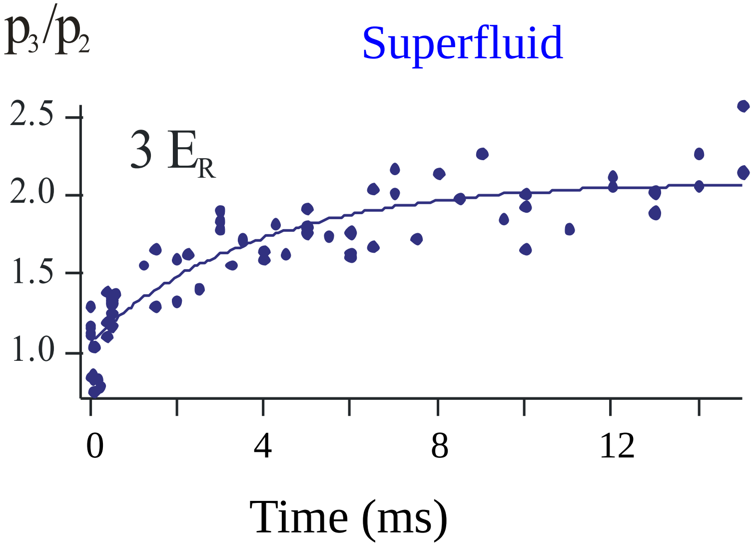
Exact diagonalization is excluded with two atoms per site

(too many configurations for even a few sites)

2- At lower lattice depths (in the superfluid regime)

One tunes the relative strength of the different exchange processes by tuning lattice depth





Large lattice depth: dipolar exchange and contact exchange contribute on different timescales

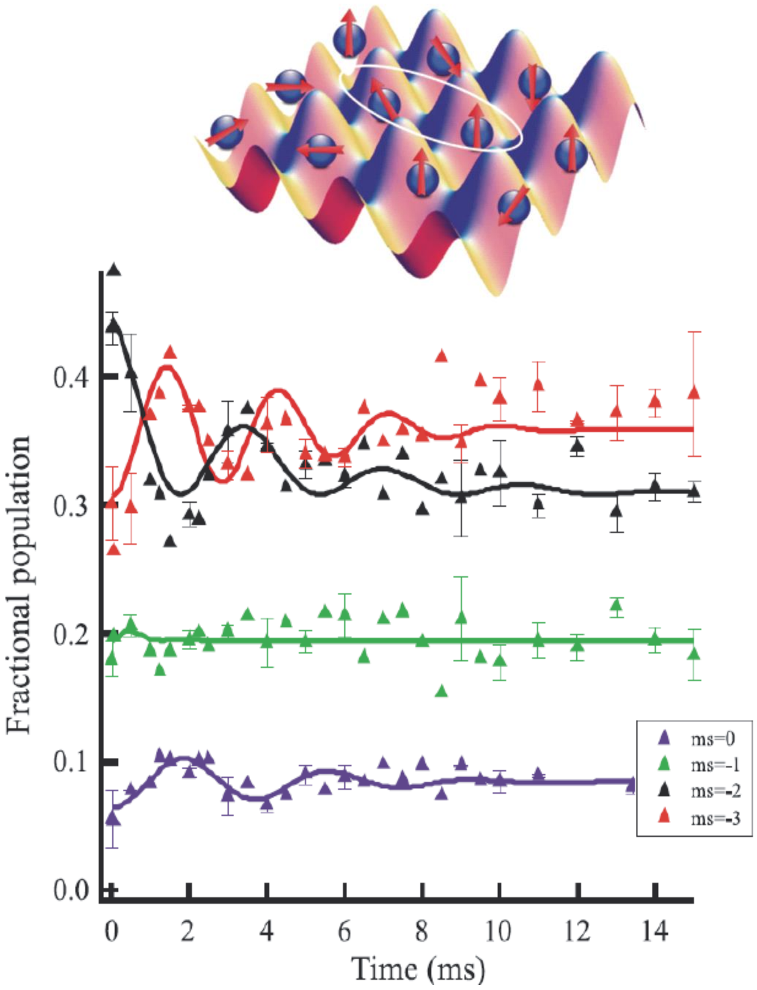
Lower lattice depth: super-exchange may occur and compete

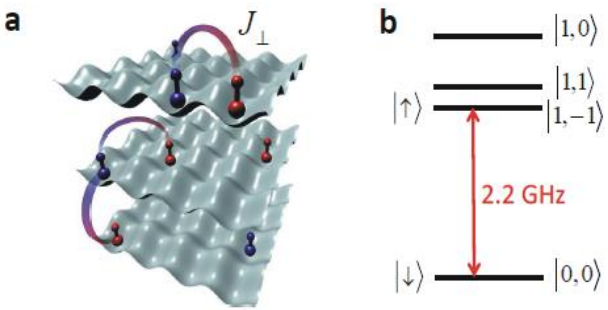
<u>In the intermediate regime:</u>

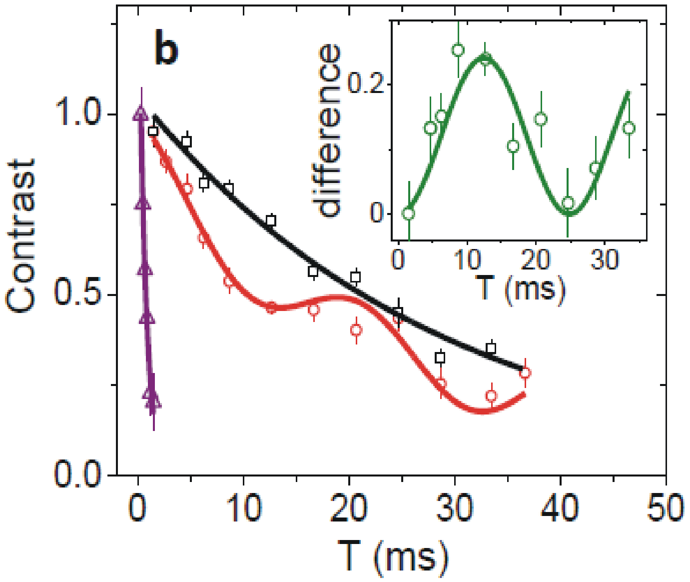
No theoretical model yet
All three exchange mechanisms contribute

Phys. Rev. A 93, 021603(R) (2016)

A unique and exotic situation!!







LPL - Paris

Boulder

$$\left(S_{1z}.S_{2z}-\frac{1}{4}(S_{1+}S_{2-}+S_{1-}S_{2+})\right)\left(1-3z^{2}\right)$$

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

Large spin; transport possible

Control of Hamiltonian possible

More probes to characterize mean-field vs « many-body » dynamics

At the mean-field level, dipolar interactions cancel out for an homogeneous system

$$\Gamma(r) = \int dr' V_{dd}(r-r')n(r') \qquad\qquad \int d\Omega V_{dd} = 0$$

Spin dynamics is a border effect

True many-body Hamiltonian predicts non-vanishing spin dynamics

$$\boxed{\left(S_{1z}.S_{2z} - \frac{1}{4}(S_{1+}S_{2-} + S_{1-}S_{2+})\right)\left(1-3z^2\right)}$$

$$\left|2,2,....,22\right\rangle \rightarrow \propto \sum_{(i,j)} V_{(i,j)} \left|2,2,...2,\underset{(i)}{1},2,...2,\underset{(j)}{3},2,2\right\rangle \qquad\qquad \Gamma = \sqrt{\sum_{(i,j)} \left(V_{(i,j)}{}^2\right)}$$

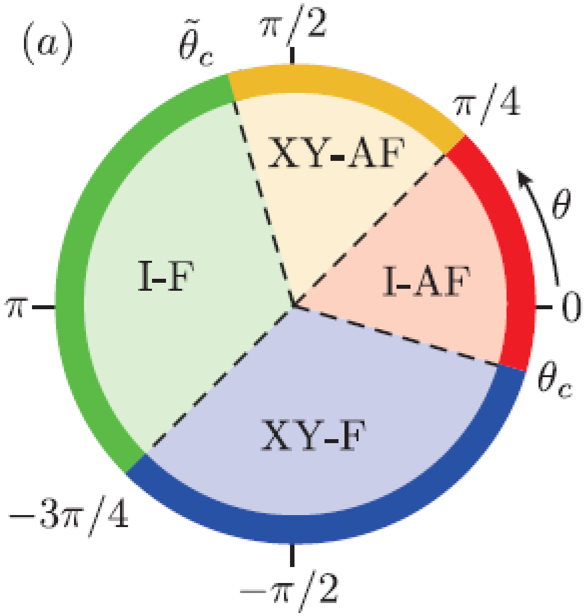
Spin dynamics occurs in the core

Implies correlations ?? How to reveal entanglement ?

(collaboration Perola Milman; Paris 7 University)

Proposals and outlook

Anomalous spin behavior



$$H = \frac{Ja^3}{\hbar^2}\sum_{i\neq j}\frac{\cos\theta\, S_i^z S_j^z + \sin\theta\left(S_i^x S_j^x + S_i^y S_j^y\right)}{|\mathbf{R}_i - \mathbf{R}_j|^3}$$

Possibility of long-range ferromagnetic order in 2D (in contrast to Mermin Wagner theorem for short-range interactions)

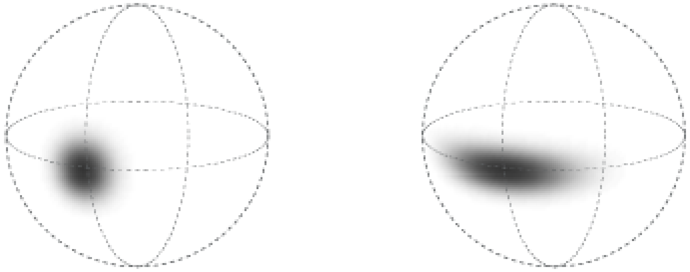
Buchler PRL **109**, 025303 (2012)

Spin-orbit coupling when agnetization is free

(Rey, Buchler, Zoller, Karr, Lev…)

Needs to engineer two degenerate states of different magnetization

Spin-squeezing after tilting the spins



(on-going collaboration with A. M. Rey)

Outline

I Spinor physics when spin arrises both from nuclear and electronic spins

The importance of spin-dependent interactions

II **Dipolar spinor physics** when the spin is purely electronic

The importance of dipole-dipole interactions

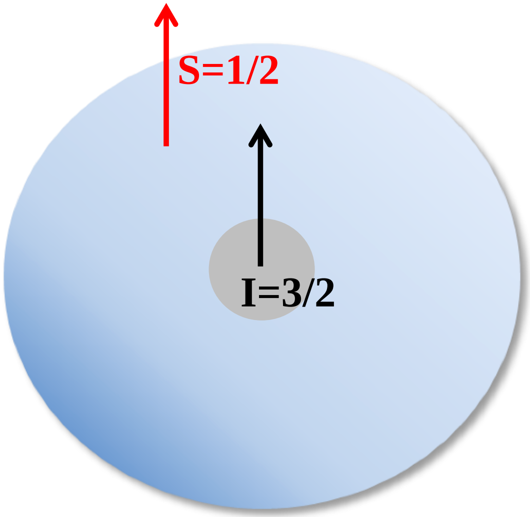
III **SU(N) magnetism** when the spin is purely nuclear

The effects of a new symmetry

Atoms are composite objects, whose spin can be larger than 1/2

$$\vec{F} = \vec{S} + \vec{I}$$

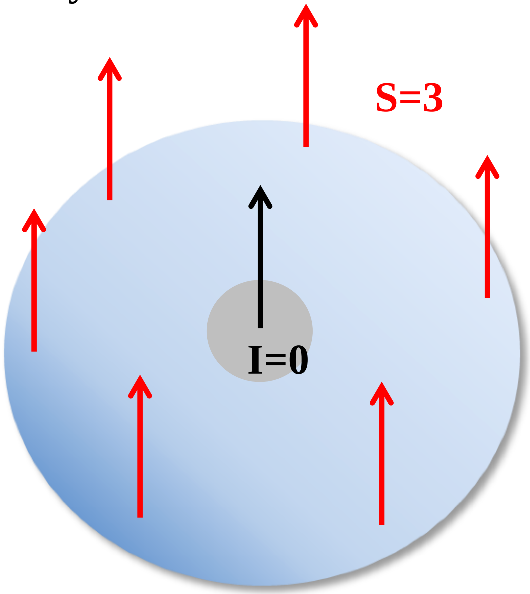
Alkali: spin arrises both from nuclear and electronic spins



e.g. Na, Rb

Spin-dependent
contact interactions

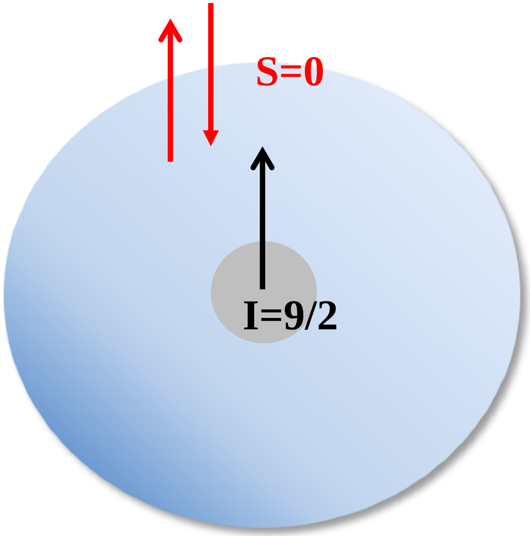
« magnetic atoms »: spin is purely electronic



e.g. Cr, Er, Dy

Strong dipole-dipole
long-range interaction

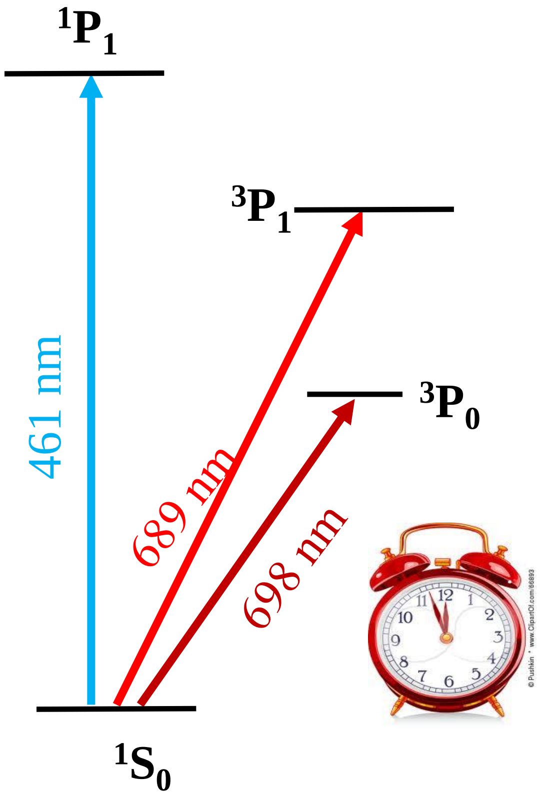
Alkaline-earth: spin is purely nuclear



e.g. Sr, Yb

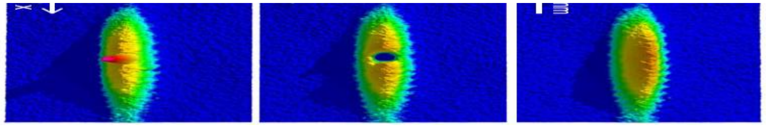
Spin-independent
contact interactions

Introduction to alkaline-earth atoms



Zero electronic spin: no magnetic field sensisivity

Narrow-line laser cooling



Reach degeneracy by simple laser-cooling! (Schreck)

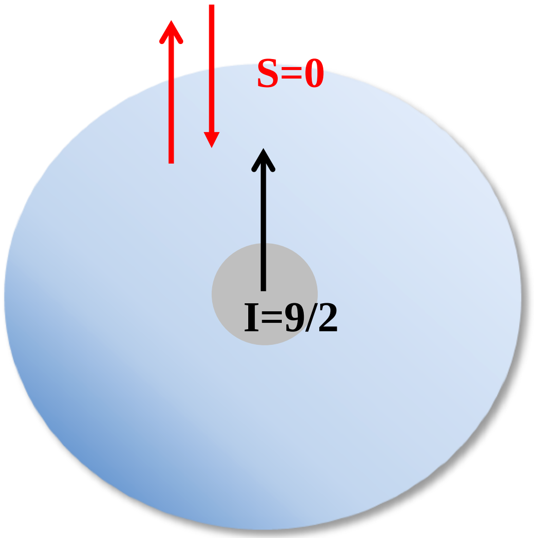
Extremely narrow line

Clock transition

Possibility of a Q-bit in the THz regime

Applications to quantum information

Fermionic isotope in the ground state:
SU(N) symmetry



e.g. Sr, Yb

Spin entirely due to nucleus

Spin-independent interactions

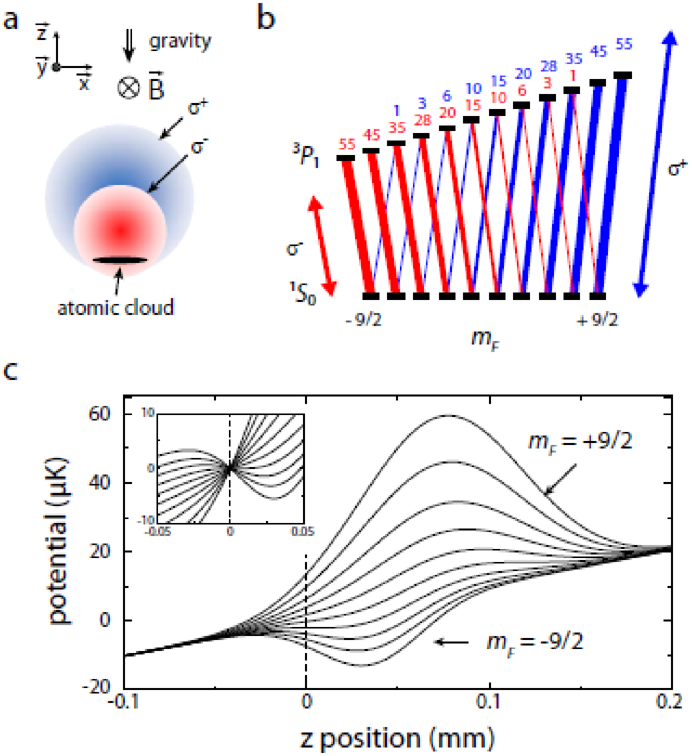
One obvious consequence : non spin-exchange dynamics

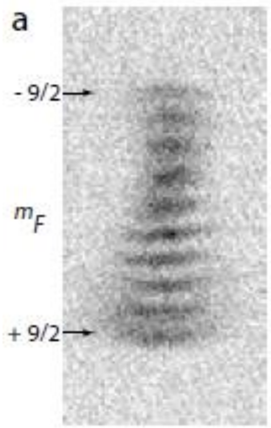
- Nothing happens ? Boring ?

- Can prepare arbitrary number of « colours » in the system.

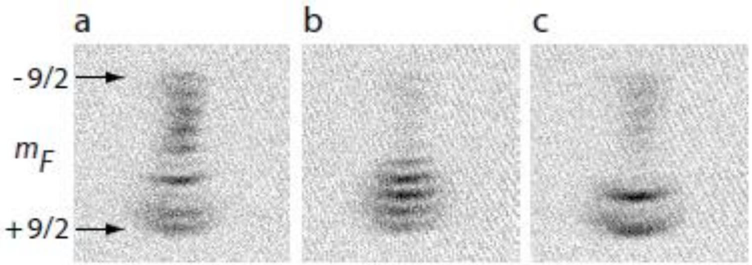
How to measure ? Optical Stern-Gerlach technique

Takahashi, Schreck





Control using optical pumping

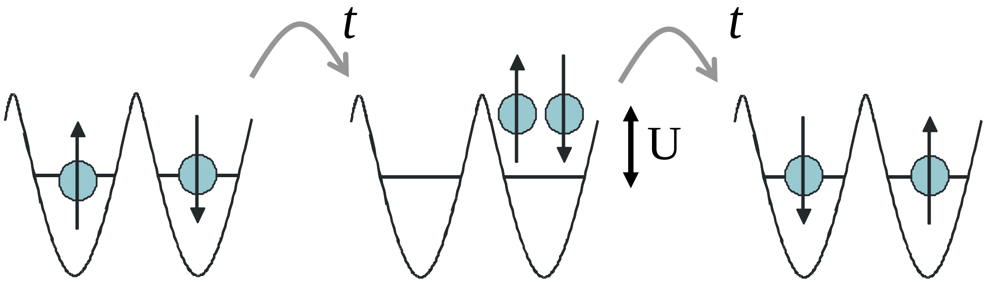


Schreck, Takahashi

No spin dynamics → very useful tool for spin preparation to study SU(N=2 to 10) physics

Proposal : interplay between SU(N) magnetism and lattice topology

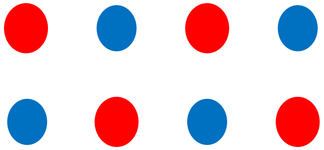
Reminder: SU(2) case. Two atoms in different states can reduce their energy by tunneling

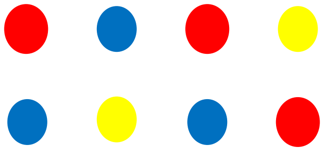


$$\Gamma = -\frac{t^2}{U}$$

Examples:

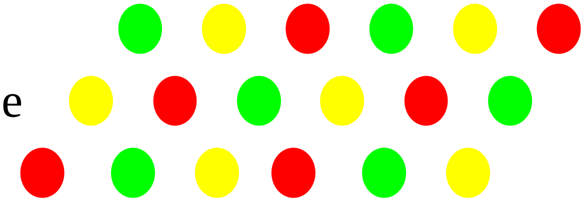
2 colors
Square
Ordered





3 colors
Square
Dis-ordered

3 colors
Triangular lattice
Ordered

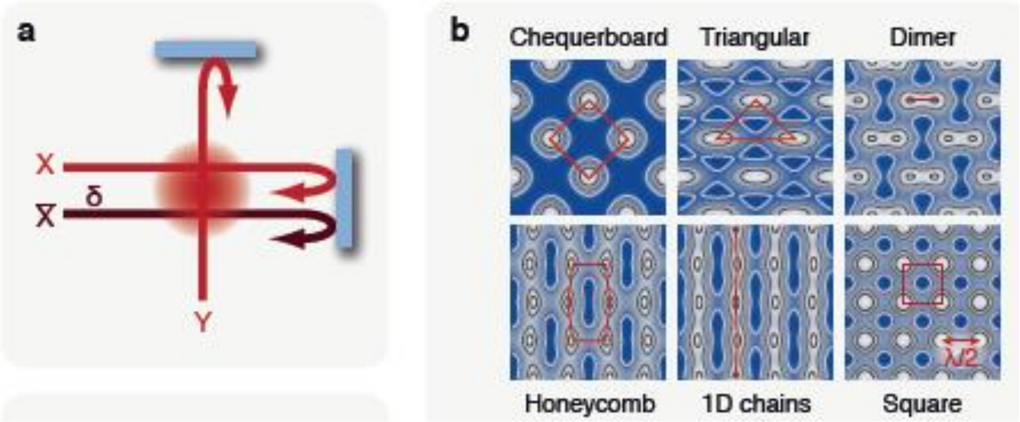


Frederic Mila

For a square lattice:
SU(2) ordered
SU(3 and 4) disordered
SU(5) ordered (very low T's)
SU(6) disordered...
Honeycomb and Kagomé lattice very interesting for SU(N=3,4).

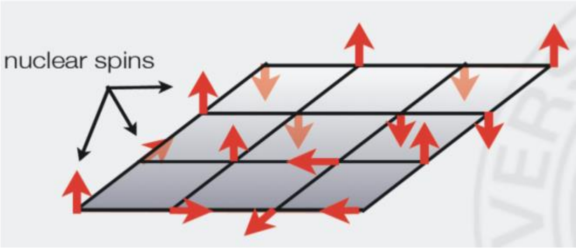
Proposal : interplay between SU(N) magnetism and lattice topology

One can use lattice with tunable topology, using « simple » beam arrangements



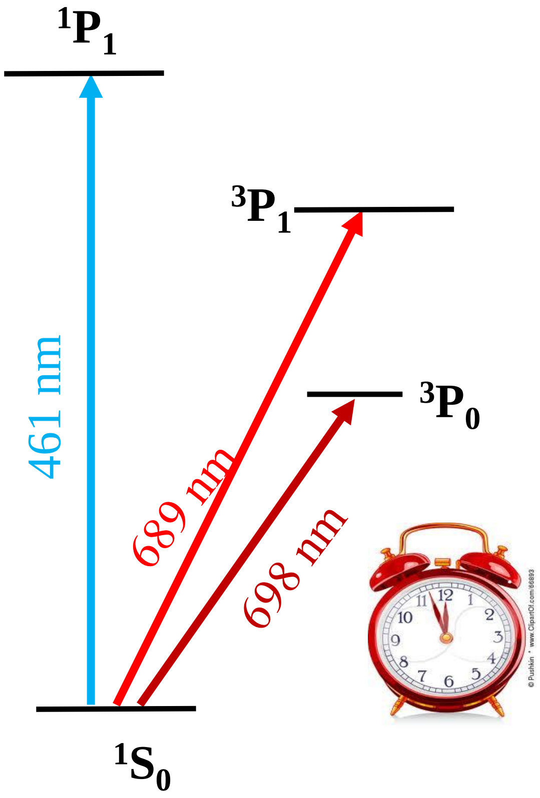
Esslinger

SU(N) symmetry introduces large degeneracies in gound state
Possibilities of spin liquids
(→Effet Hall, frustration, anomalous transport properties…)



Rey, Gorshkov,…

What about Feshbach resonances ?



Spin singlet in the ground state. Weak magnetic field sensitivity.

Maybe existence of very very narrow Feshbach resonances at large magnetic fields ??

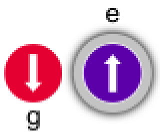
Otherwise, need to excite an other (orbital) degrees of freedom.

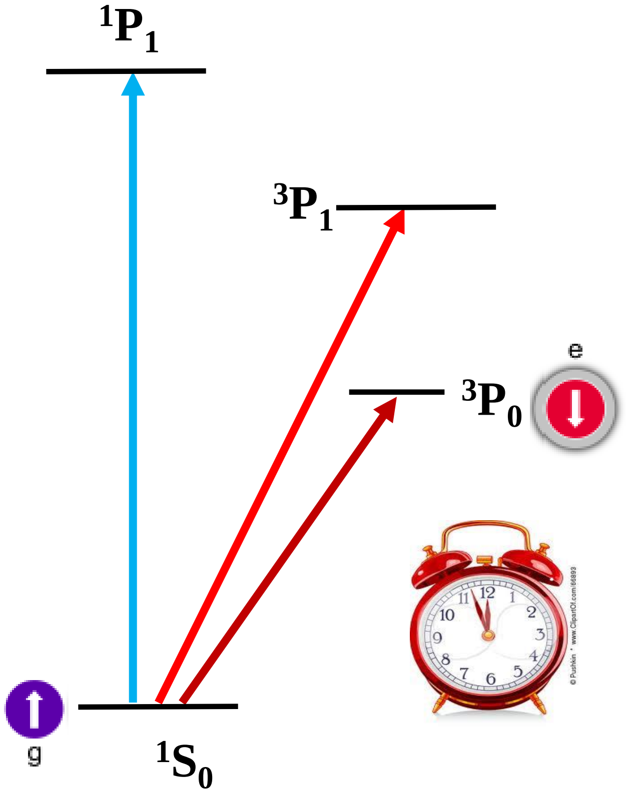
Possibilities for optical Feshbach resonances ?

See T. Killian. Modification of scattering length is possible, at the expense of a much reduced lifetime. Other possibilities may arise using the clock transition.

« Orbital » SU(N) magnetism

One prepares a mixture





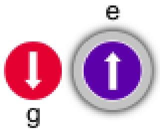
Two possible anti-symmetric states

$$|eg^+\rangle = \left(|eg\rangle + |ge\rangle\right) \otimes \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$

$$|eg^-\rangle = \left(|eg\rangle - |ge\rangle\right) \otimes \left(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\right)$$

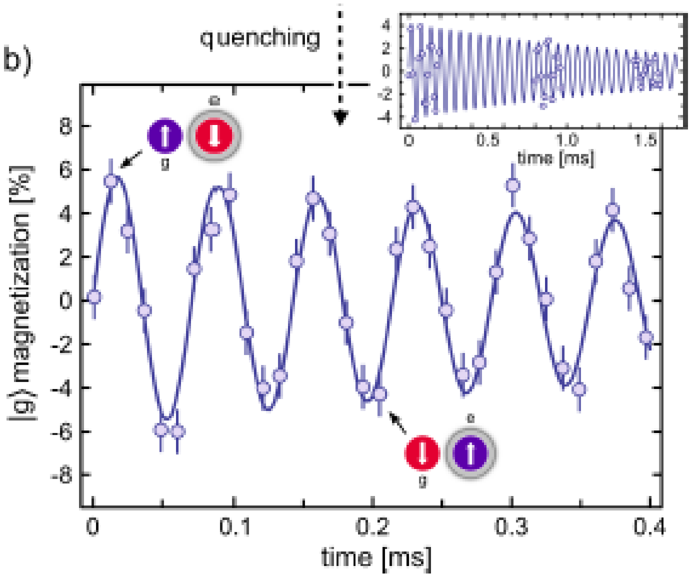
$$\boxed{a_{eg^+} \neq a_{eg^-}}$$

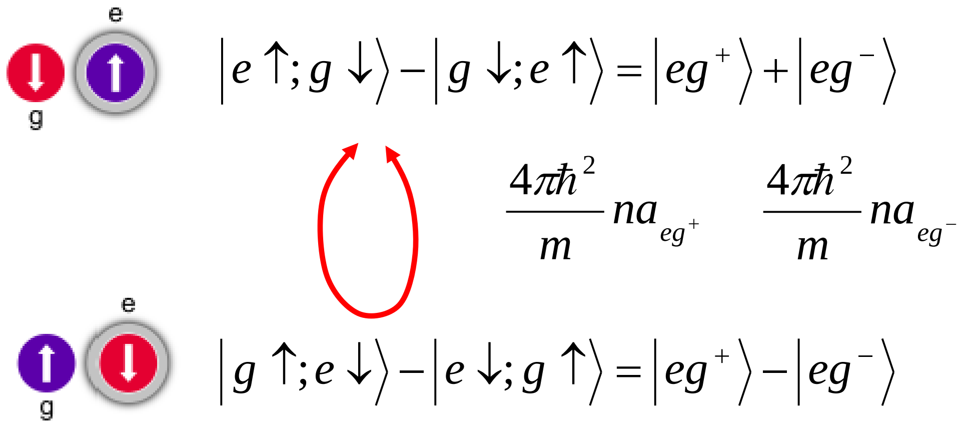
$$|e\uparrow; g\downarrow\rangle - |g\downarrow; e\uparrow\rangle = |eg^+\rangle + |eg^-\rangle$$



« Orbital » SU(N) magnetism

Observation of exchange interactions for a mixture in 1S0 3P0





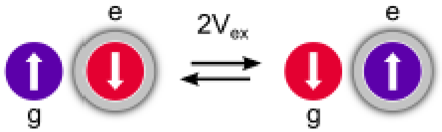
$$|e\uparrow; g\downarrow\rangle - |g\downarrow; e\uparrow\rangle = |eg^{+}\rangle + |eg^{-}\rangle$$

$$\frac{4\pi\hbar^{2}}{m} n a_{eg^{+}} \qquad \frac{4\pi\hbar^{2}}{m} n a_{eg^{-}}$$

$$|g\uparrow; e\downarrow\rangle - |e\downarrow; g\uparrow\rangle = |eg^{+}\rangle - |eg^{-}\rangle$$

(Ye, Bloch, Fallani, 2015)

$$\Gamma = \frac{4\pi\hbar^{2}}{m} n\left(a_{eg^{+}} - a_{eg^{-}}\right)$$

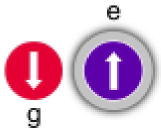


Although the spin is purely nuclear, there is spin-exchange in practice because there are two molecular potentials associated to the two possible orbital states

« Orbital » SU(N) magnetism

Orbital Feshbach resonance

We again consider a mixture



$$|eg^{+}\rangle = \left(|eg\rangle + |ge\rangle\right) \otimes \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$

$$|eg^{-}\rangle = \left(|eg\rangle - |ge\rangle\right) \otimes \left(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\right)$$

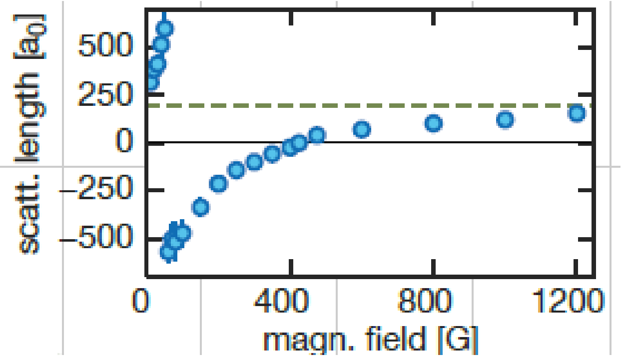
For Yb:

$$\boxed{a_{eg^{+}} > 2000 a_0}$$

Existence of a very weakly bound molecular state

$$\frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$ Insensitive to B

$$\frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\right)$$ **Weakly sensitive to B !!**



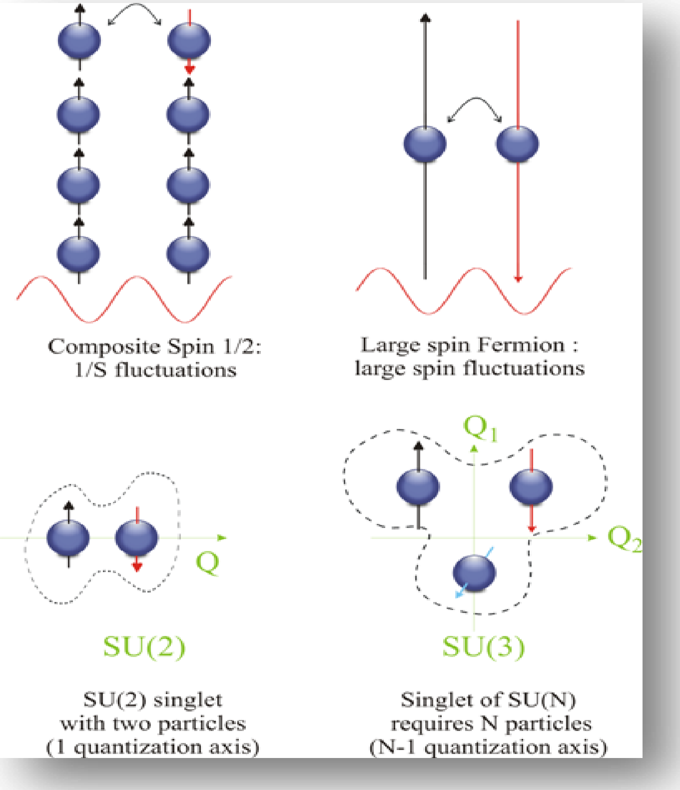
(Bloch, Fallani, 2015)

Proposals to investigate Kondo physics

Other fundamental aspects of high spin fermions

Increased spin fluctuations

SU(N) symmetry implies new conservation laws.
For example, no spin dynamics
There exists
N-1 quantization axis !
One singulet takes N atoms



Wu

Non singlet pairing « non-singulet » **(→ ^{3}He)**

Particle clustering; competition between superfluidity and clustering…

Hofstetter,…

Conclusion – Large Spin Magnetism

Spin-dependent interactions

Spin dynamics introduces beyond mean-field effects,
Squeezing, non-classical states…

« True » « non-classical » ground state hasn't been reached
Condensate of pairs, fragmentation…

Lots of interesting new excitations
(e.g. non Abelian, non-trivial topology…)

Dipolar systems

Anomalous Spin models are being studied
Beyond mean-field effects are obtained for spin-dynamics in lattices
Spin ordering in the ground state hasn't been reached

Large spin fermions

First experimental data available
New pairing mechanism
New Fermi liquid properties
SU(N) magnetism ahead

Need to better cool the spin degrees of freedom
Use the spin degrees of freedom to cool ?