Large Spin (quantum) Magnetism

B. Laburthe-Tolra

Emphasis of this talk:
- Introduction to the field and "good" proposals
- Beyond mean-field effects

Chromium dipolar gases - and Strontium project

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M. Robert-de-St-Vincent, P. Pedri

Have left: A. de Paz,A. Chotia, A. Sharma, B. Pasquiou , G. Bismut, M. Efremov, Q. Beaufils,
J. C. Keller, T. Zanon, R. Barbé, A. Pouderous, R. Chicireanu

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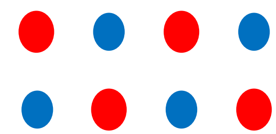
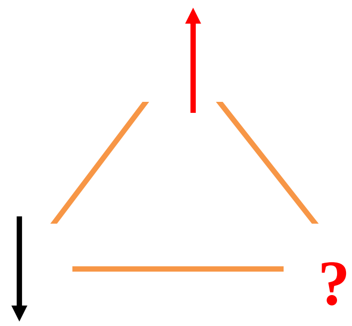
Quantum magnetism, some paradigms from solid-state physics
Strongly correlated (s=1/2) electrons

Condensed matter physics ↔ many-body quantum physics

High-Tc superconductivity ⟷ Antiferromagnetism Hubbard model





Frustrated magnetism

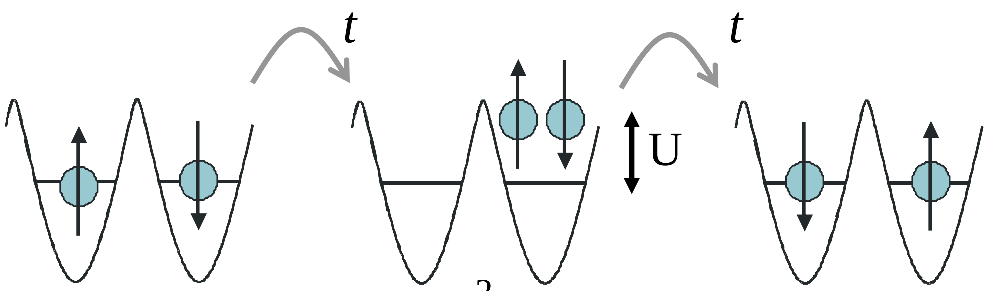
Spin liquids

Heavy fermions (Kondo physics), anomalous superconductivity

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

From spin ½ to large spins

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



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

Super- Exchange (I)

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

Ising Exchange

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

Cold atoms revisit paradigms from solid-state physics experimentally.

(effective spin ½: Esslinger, Hulet, Bloch, Greiner, Porto, Ketterle, Monroe…)

What about s>1/2 ?? (Stamper-Kurn, Lett, Klempt, Chapman, Sengstock, Shin, Gerbier, …)

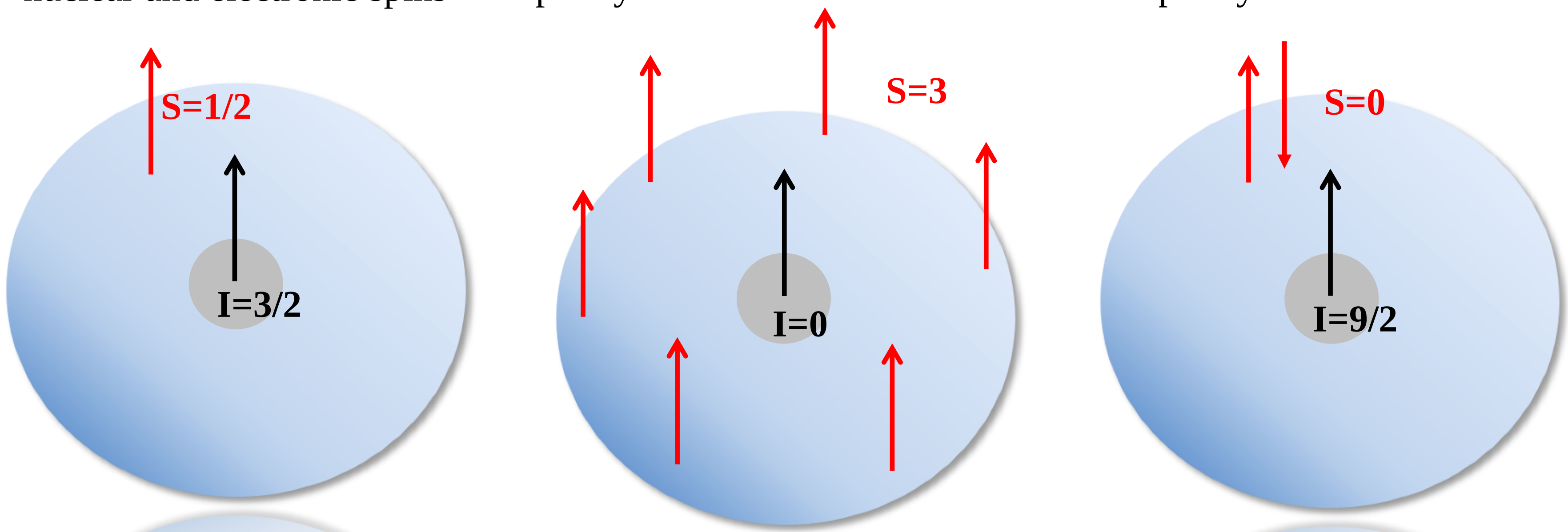
Atoms are composite objects, whose spin can be larger than 1/2

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

Alkali: spin arrises both from nuclear and electronic spins

« magnetic atoms »: spin is purely electronic

Alkaline-earth: spin is purely nuclear



e.g. Na, Rb

e.g. Cr, Er, Dy

e.g. Sr, Yb

Spin-dependent
contact interactions

Strong dipole-dipole
long-range interaction

Spin-independent
contact interactions

Outline

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

The importance of spin-dependent interactions

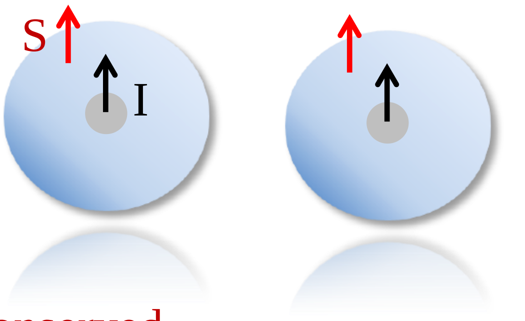
II **Dipolar spinor physics** when the spin is purely electronic

The importance of dipole-dipole interactions

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

The effects of a new symmetry

How two spin-full atoms collide



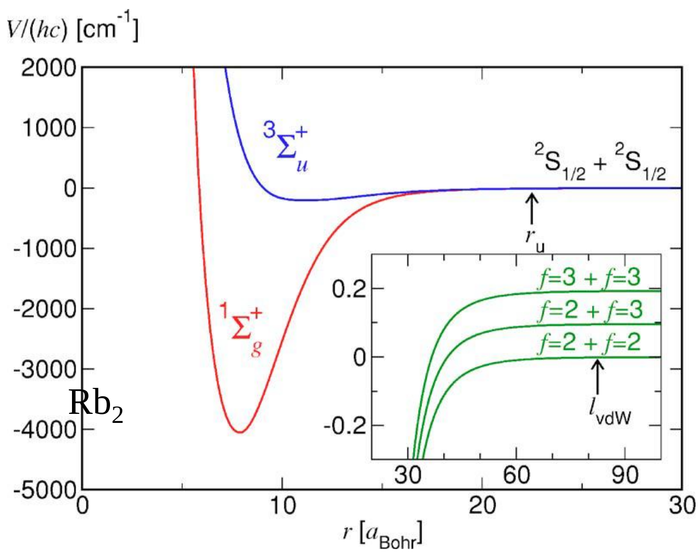
$$\vec{F}_{tot} = \vec{F}_1 + \vec{F}_2 = \vec{S}_1 + \vec{I}_1 + \vec{S}_2 + \vec{I}_2$$

- 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

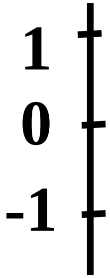
Van-der-Waals (contact) interactions

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

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

(mean-fisld) Spinor phases driven by spin-dependent contact interactions
Example: spin 1 atoms

f=1. Three Zeeman states

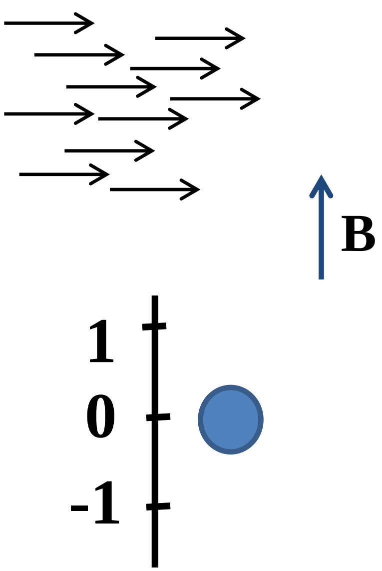


Two molecular potentials F=0,2 ; two scattering lengths: a_0, and a_2.

If $a_2 < a_0$: spins align : ferromagnetic

If $a_2 > a_0$: polar phase

BECS



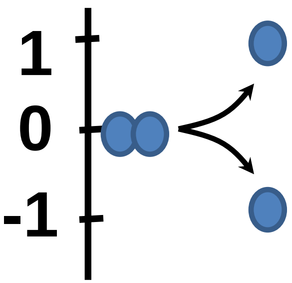
Ho 1998 ; Machida 1998

Experiments : Lett, Chapman, Sengstock, Stamper-Kurn, Ketterle, Gerbier…

Spin-dependent interactions drive spin dynamics

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

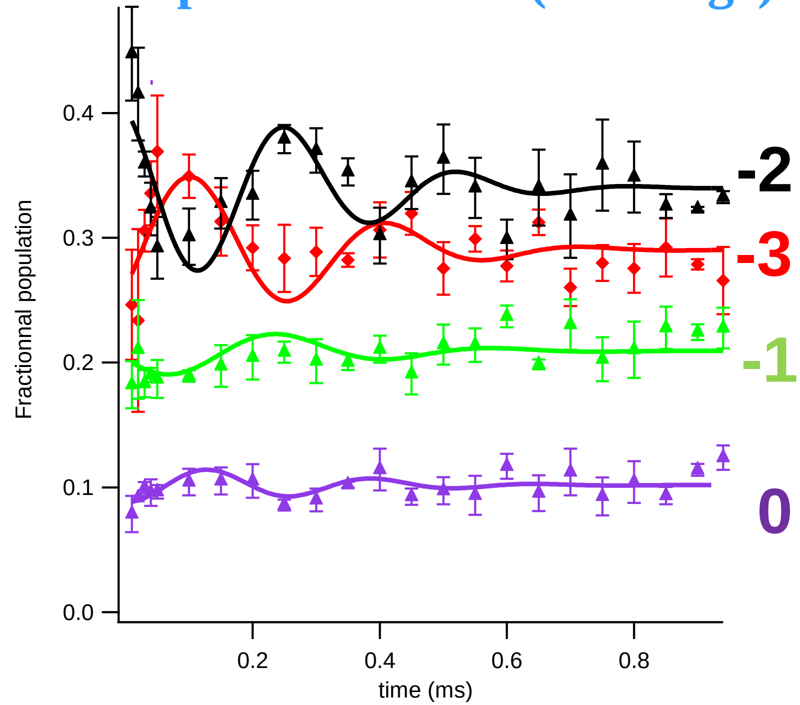
$$\frac{-1}{\sqrt{3}}\left| S_t=0, m_S=0 \right\rangle + \sqrt{\frac{2}{3}}\left| S_t=2, m_S=0 \right\rangle$$



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

Contact exchange (III)

Spin oscillations (exchange)



Magnetism… at constant magnetization

linear Zeeman effect does not matter

Spin-changing collisions have no analog in spin ½ systems

Can directly probe dynamics by measuring spin populations

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!**

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

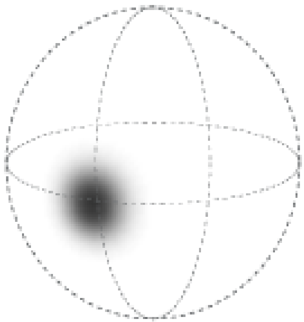
Two-body physics obviously does predics **spin dynamics**

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

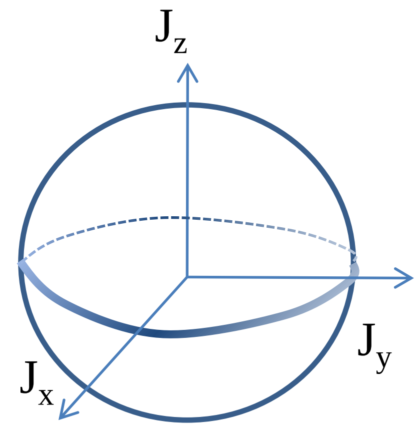
$$\left|0,0\right\rangle \leftrightarrow \frac{1}{\sqrt{2}}\left(\left|1,-1\right\rangle + \left|-1,1\right\rangle\right)$$ at rate $$\Gamma = \frac{4\pi\hbar^2}{m}(a_2 - a_0)n$$

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

Spin dynamics and beyond mean-field effects

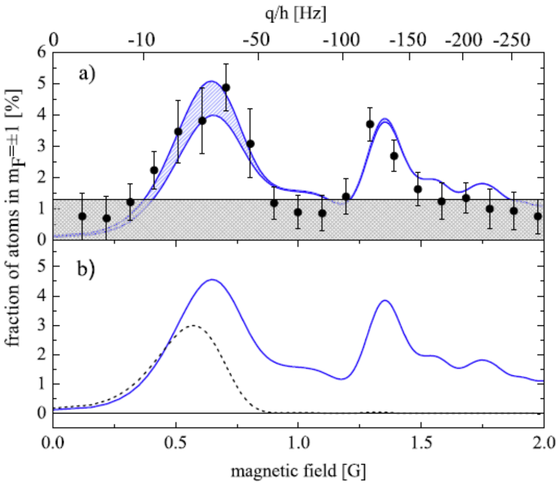


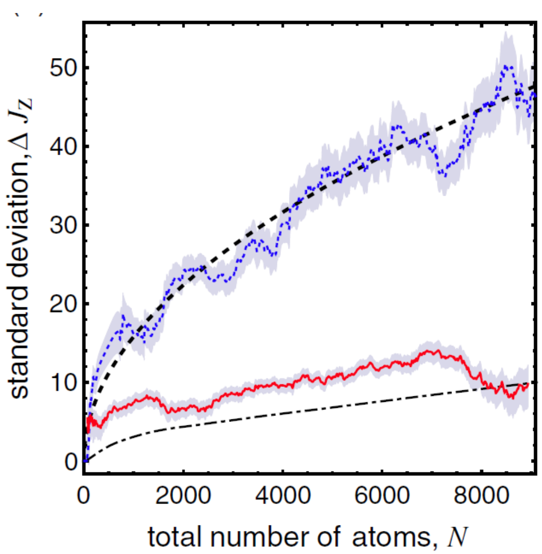
$$|0,0\rangle \leftrightarrow \frac{1}{\sqrt{2}}\left(|1,-1\rangle + |-1,1\rangle\right)$$

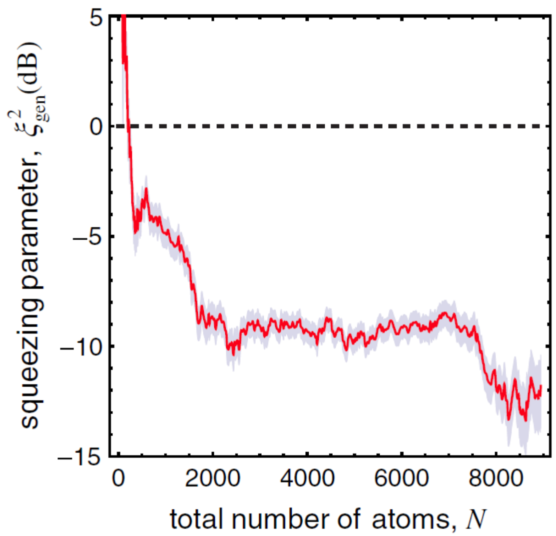


Spin dynamics generates entanglement.

Creates twin beams which may be useful for atom interferometry







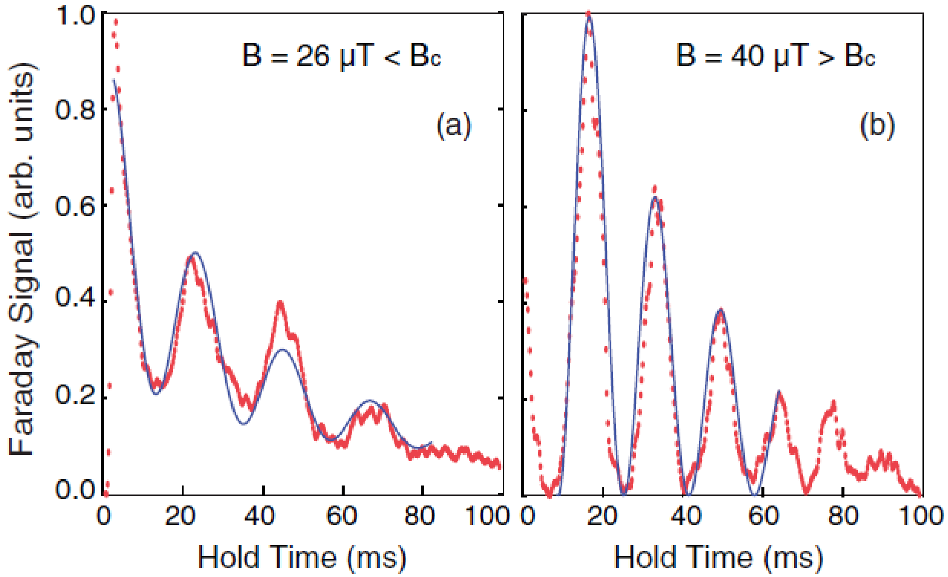
Karsten Klemt, Hannover: twin beams useful for interferometry ? EPR tests ?

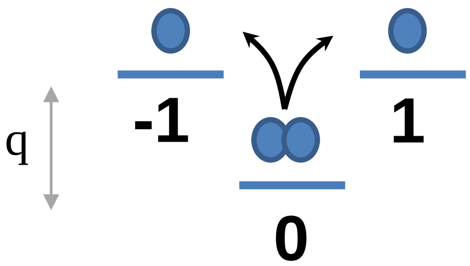
(also M. Chapman)

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





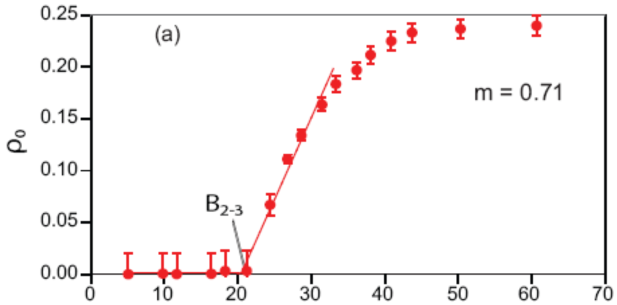
P. Lett

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)

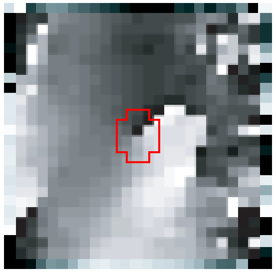


Stamper-Kurn, Lett, Gerbier

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

Quench through phase transitions

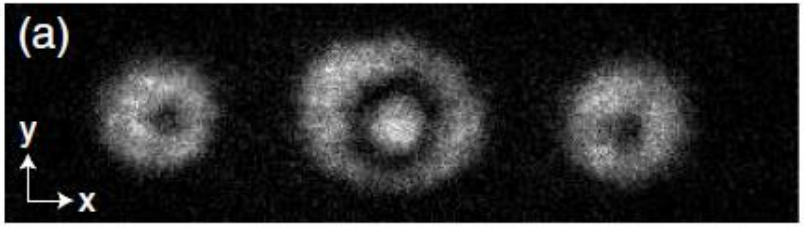
Here, generation of topological defects

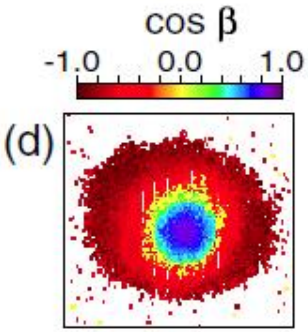


Stamper-Kurn

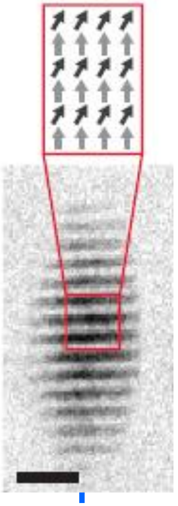
Domains, spin textures, spin waves, topological states

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

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

Creates a pair

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

Pair condensate is the real ground state !

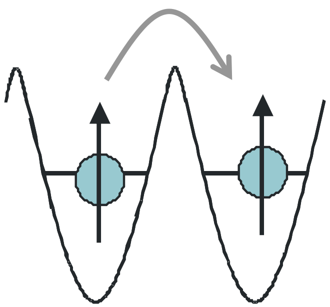
a2<a0: Ferromagnetic; Spontaneous symmetry breaking

See Bigelow 1998 ; Ho 2000

Yet to come: spinor gases in lattices

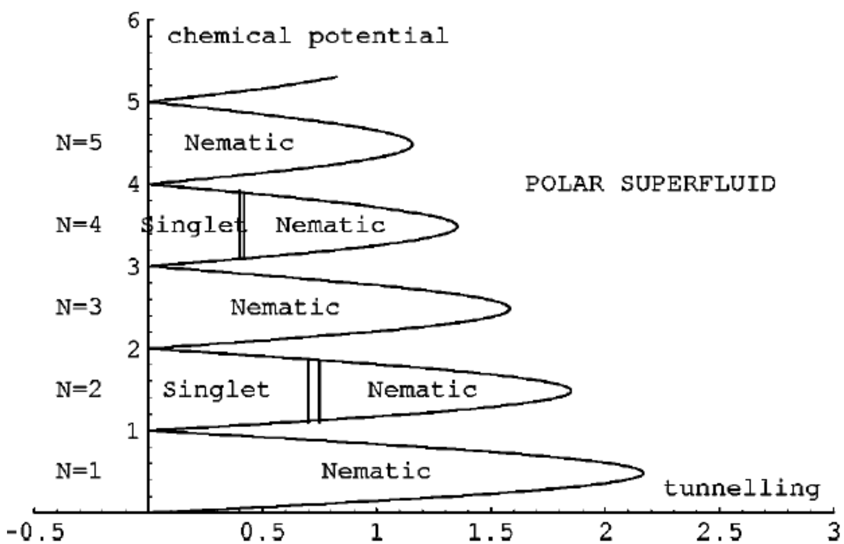
Start with two bosons in two sites (insulating states) ; allow perturbatively for tunneling

J



$$H = -J_1 \vec{S}_1 . \vec{S}_2 - J_2 (\vec{S}_1 . \vec{S}_2)^2 \qquad J_i \propto J^2 / U$$

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)

See recent expts : Phys. Rev. A 93, 063607 (2016)

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

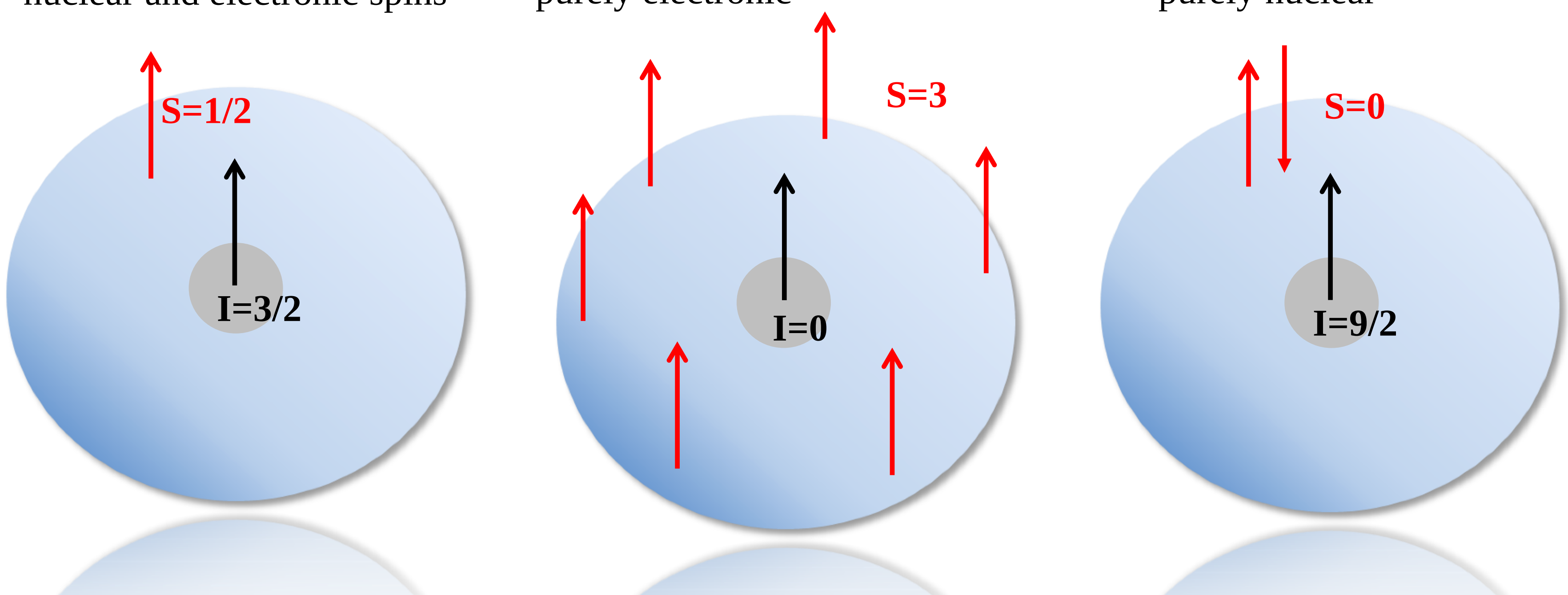
Atoms are composite objects, whose spin can be larger than 1/2

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

Alkali: spin arrises both from nuclear and electronic spins

« magnetic atoms »: spin is purely electronic

Alkaline-earth: spin is purely nuclear



e.g. Na, Rb

e.g. Cr, Er, Dy

e.g. Sr, Yb

Spin-dependent
contact interactions

Strong dipole-dipole
long-range interaction

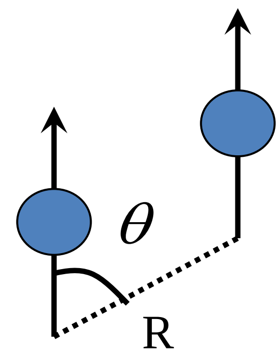
Spin-independent
contact interactions

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

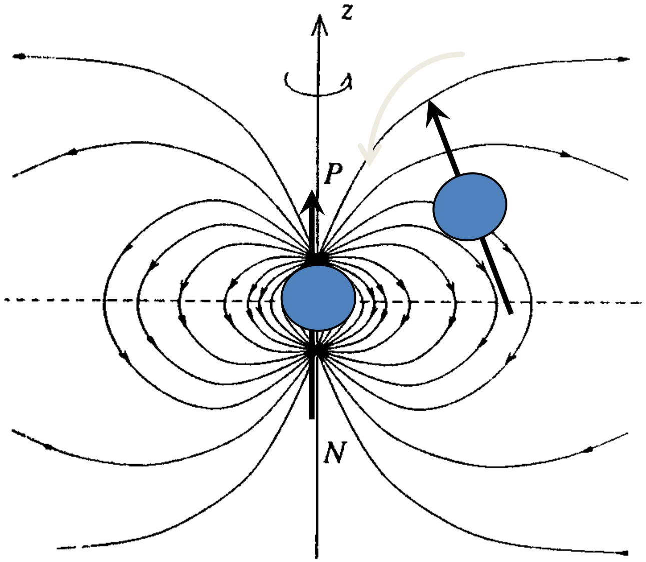
Isotropic

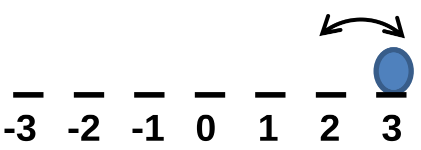
(only few experiments worldwide with non-negligible dipolar interactions
- Stuttgart, Paris, Innsbruck, Stanford, Boulder, Boston, Hong-Kong,…)

S≥3 **S=1/2**

First main feature introduced by dipolar interactions:

Free Magnetization





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

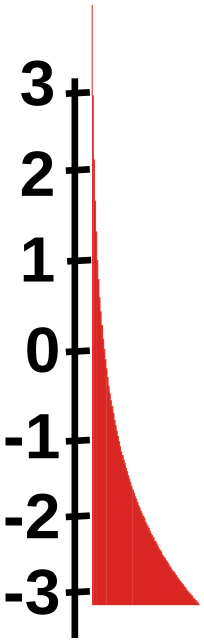
Spin temperature equilibriates with mechanical degrees of freedom

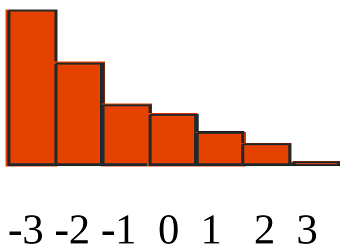
(due to magnetization changing collisions)

At low magnetic field: spin thermally activated

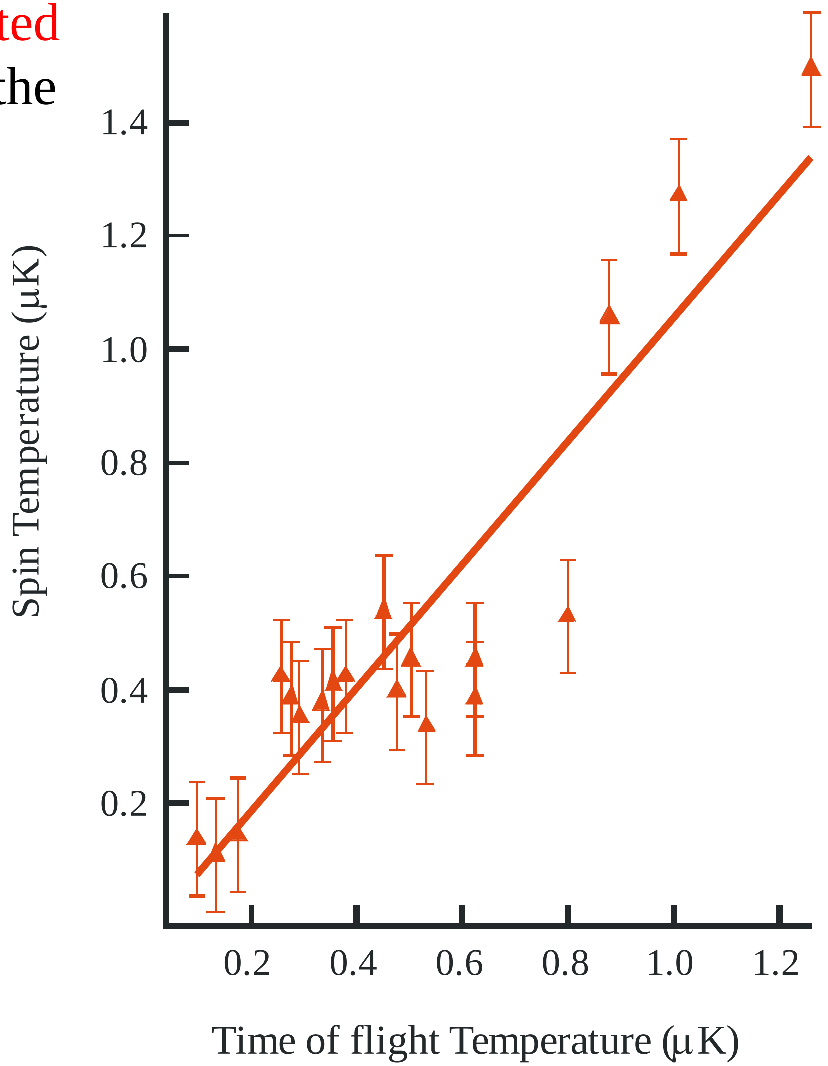
Magnetization adpats to temperature due to the presence of dipolar interactions

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





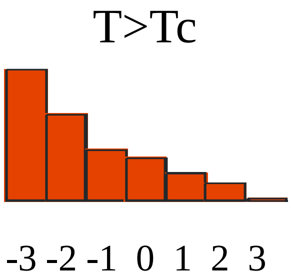
We measure spin-temperature by fitting the m_S population (separated by Stern-Gerlach technique)



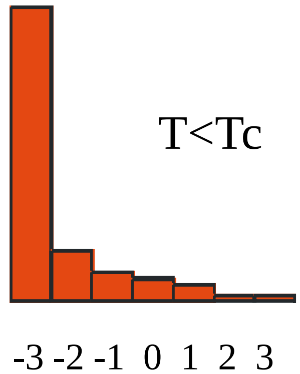
See also T. Pfau, *Nature Physics* ***2****, 765 (2006)*

Magnetic field matters !

The BEC always forms in the m_s=-3

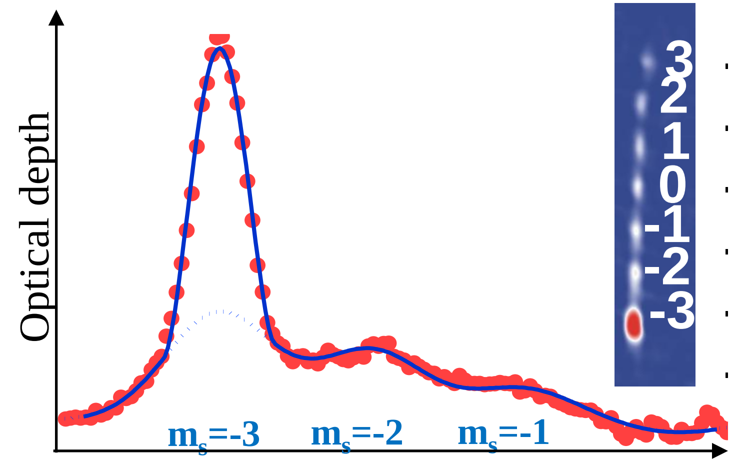


Thermal population in Zeeman excited states



a bi-modal spin distribution

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

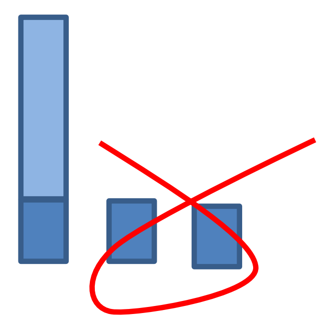


Momentum distribution in the different Zeeman states

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

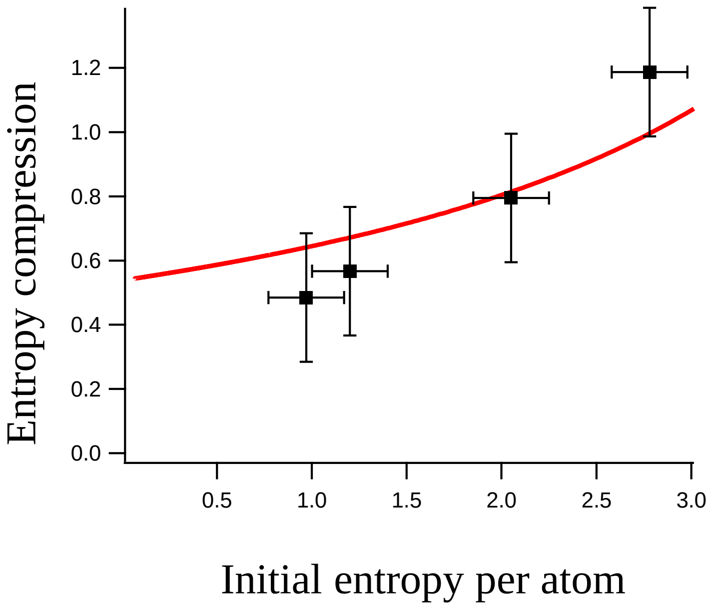
(and this process can be repeated after waiting for more depolarization)

Cooling efficiency

All the entropy lies in the thermal cloud

Thus spin filtering is extremely efficient!

In principle, cooling efficiency has no limitation

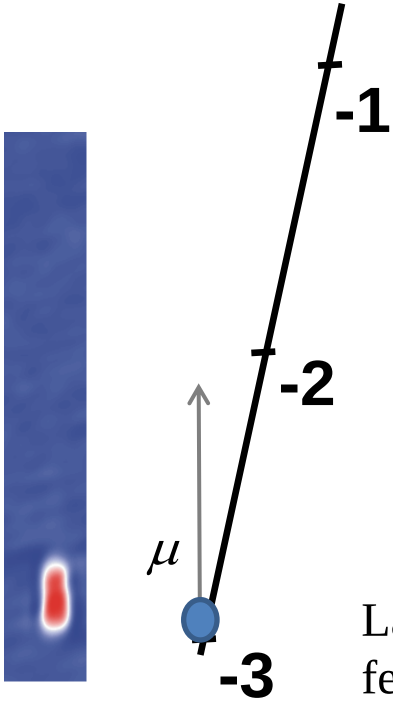


Chromium, LPL,
Phys. Rev Lett. (2015)

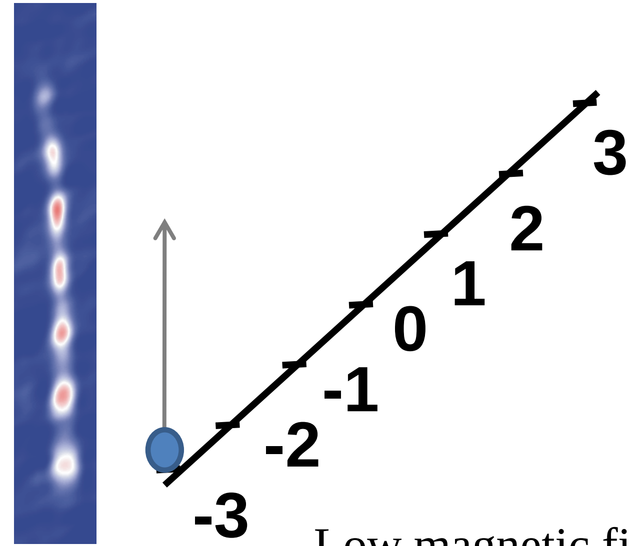
See also Rb, Stamper Kurn, Nature Physics (2015)

Use spin to store and remove entropy

New magnetic phases at low field

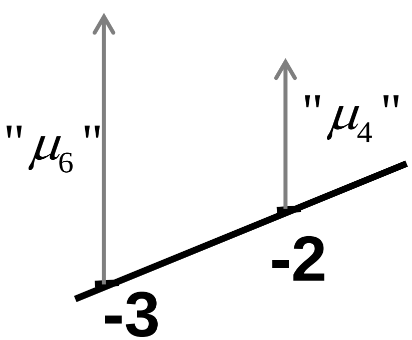


Large magnetic field :
ferromagnetic



Low magnetic field :
polar/cyclic

Observation of a phase transition due to competition between Zeeman effect and spin-dependent interactions



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

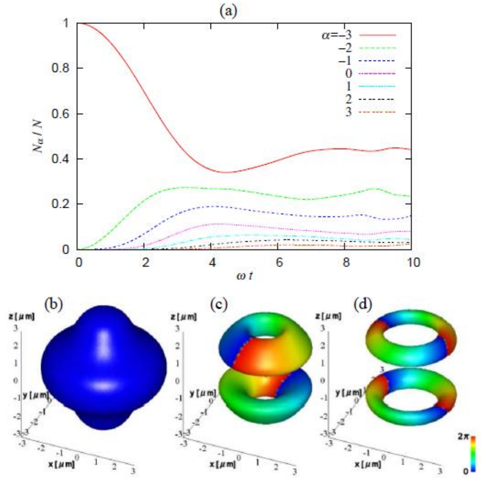
Santos PRL **96**, 190404 (2006)

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

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

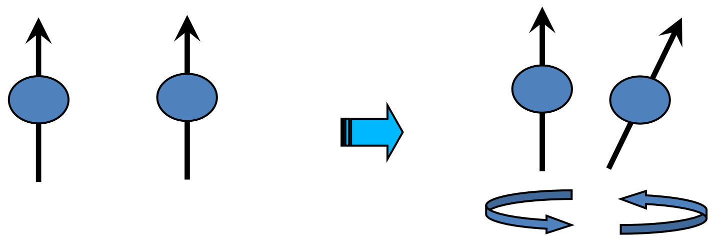
Two interesting proposals:

Einstein-de Haas effect



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

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



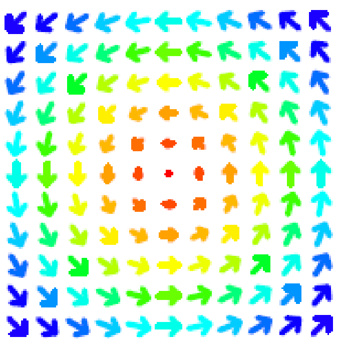
Spin-orbit coupling (conservation of total angular momentum)

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

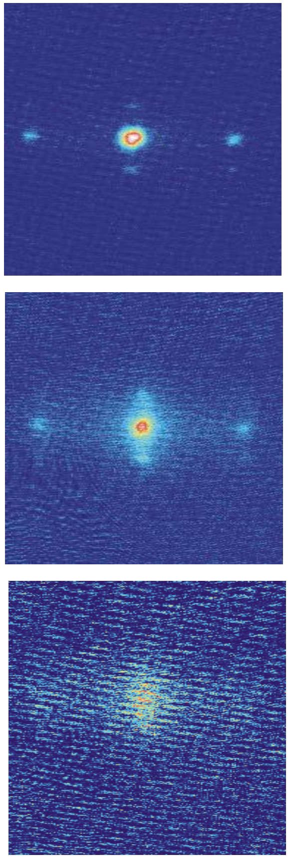
Maximize $\left|\vec{F}(\vec{k})\right|$ and $\vec{F} \perp \vec{k}$



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

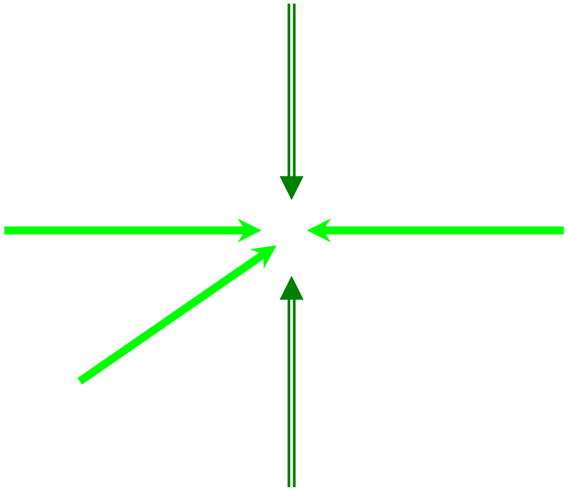
Experimental study of quantum magnetism with dipolar gases

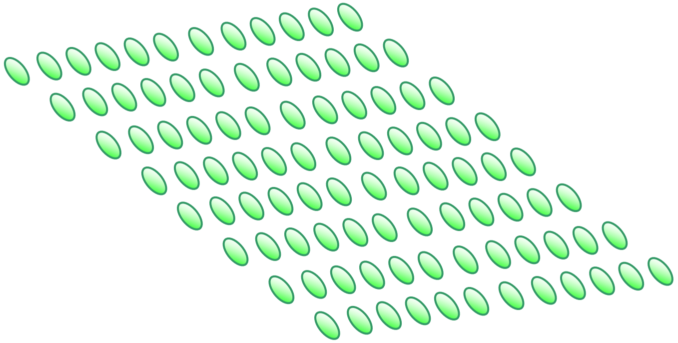
A ^{52}Cr BEC in a 3D optical lattice

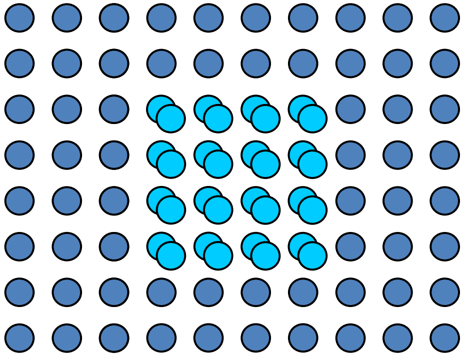


Our lattice architecture:

(Horizontal 3-beam lattice) x (Vertical retro-reflected lattice)



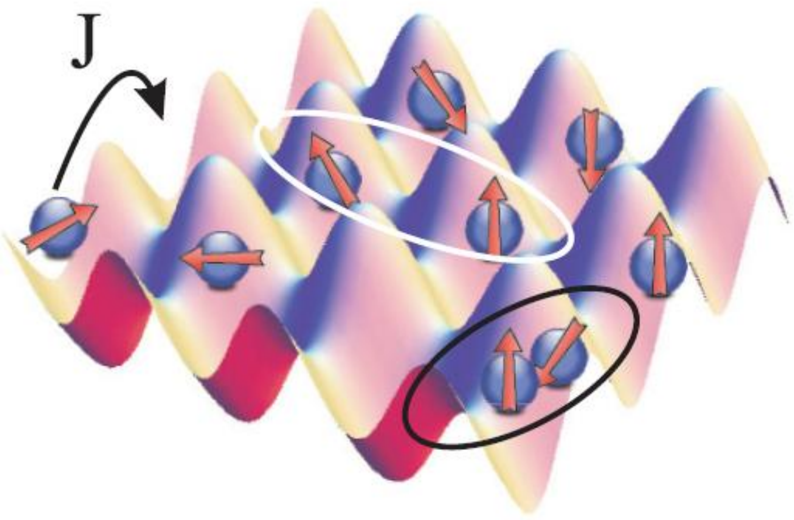




Rectangular lattice of anisotropic sites

3D lattice → Strong correlations, Mott transition…

Our System



Heisenberg model of magnetism

$$\Gamma \propto \frac{t^2}{U}\left[S_{1z}S_{2z} + \frac{1}{2}\left(S_{1+}S_{2-} + S_{1-}S_{2+}\right)\right]$$

Ising Exchange

Super- Exchange (I)

Nuclear Magnetic Resonance

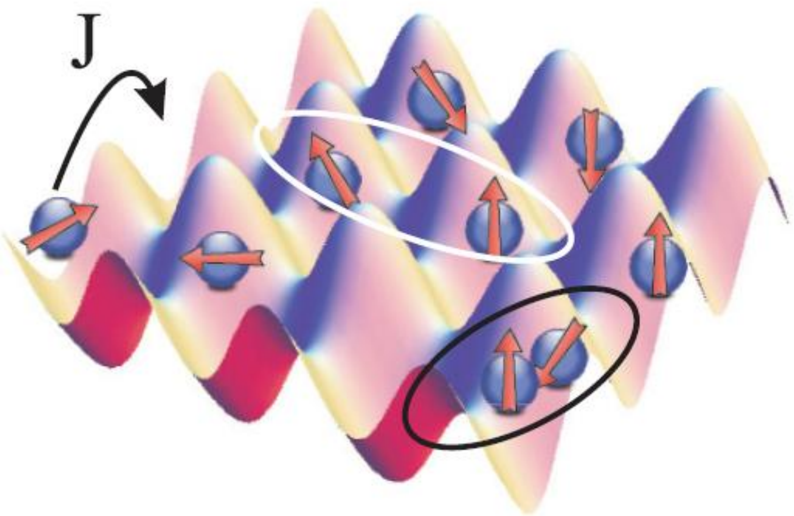
$$S_{1z}S_{2z} - \frac{1}{4}\left(S_{1+}S_{2-} + S_{1-}S_{2+}\right)$$

Dipolar Exchange (II)

(Magnetization changing collisions can be suppressed in optical lattices)

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

This Experiment

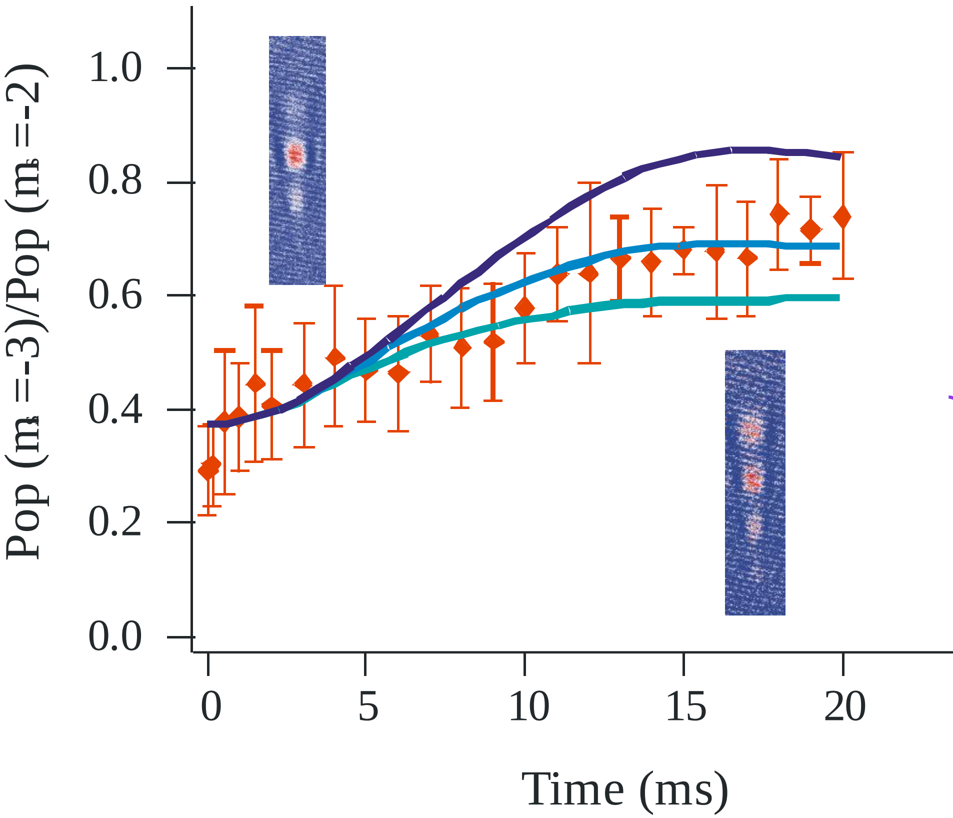


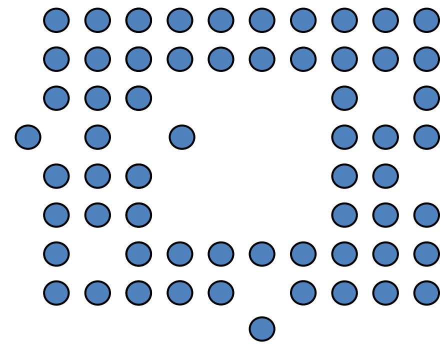
I – Excite the spins

II – Free evolution under the effect of dipolar interactions

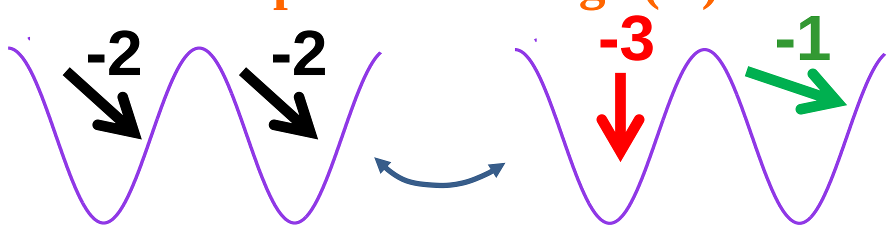
Question: Under which conditions correlations develop?

Spin dynamics after emptying doubly-occupied sites: A proof of inter-site dipole-dipole interaction





Dipolar Exchange (II)



Magnetization is constant

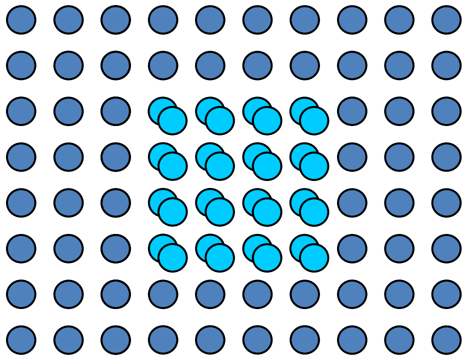
Timescale for spin dynamics = 20 ms
Tunneling time = 100 ms
Super-exchange > 10s

Experiment: spin dynamics after the atoms are promoted to ms=-2

!! Many-body dynamics !!
(each atom coupled to many neighbours)
Mean-field theories fail

Theory: exact diagonalization of the t-J model on a 3*3 plaquette (P. Pedri, L. Santos)

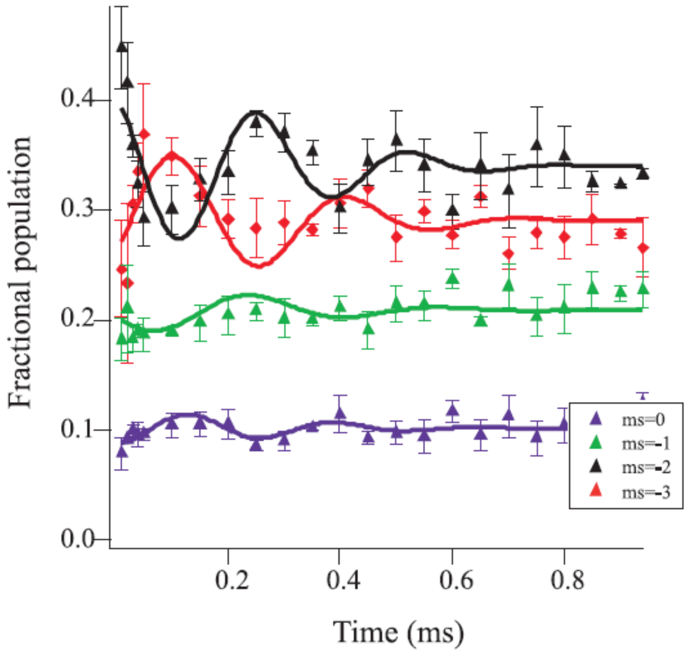
Phys. Rev. Lett., 111, 185305 (2013)

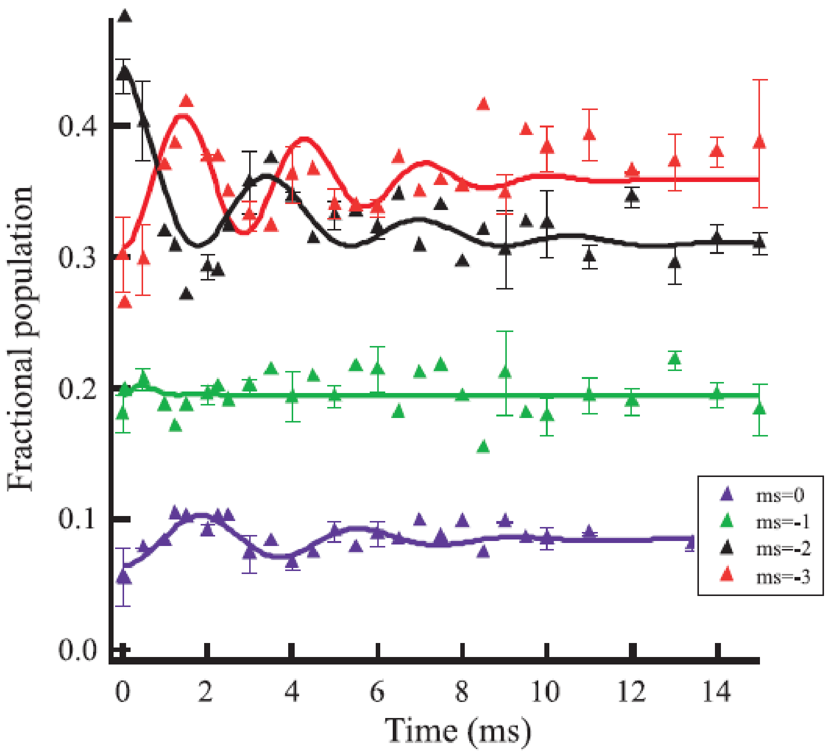


1- At large lattice depths (Mott regime)

In presence of doubly-occupied sites:
A complex oscillatory behavior dispplaying two distinc frequencies

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





Contact exchange (III)

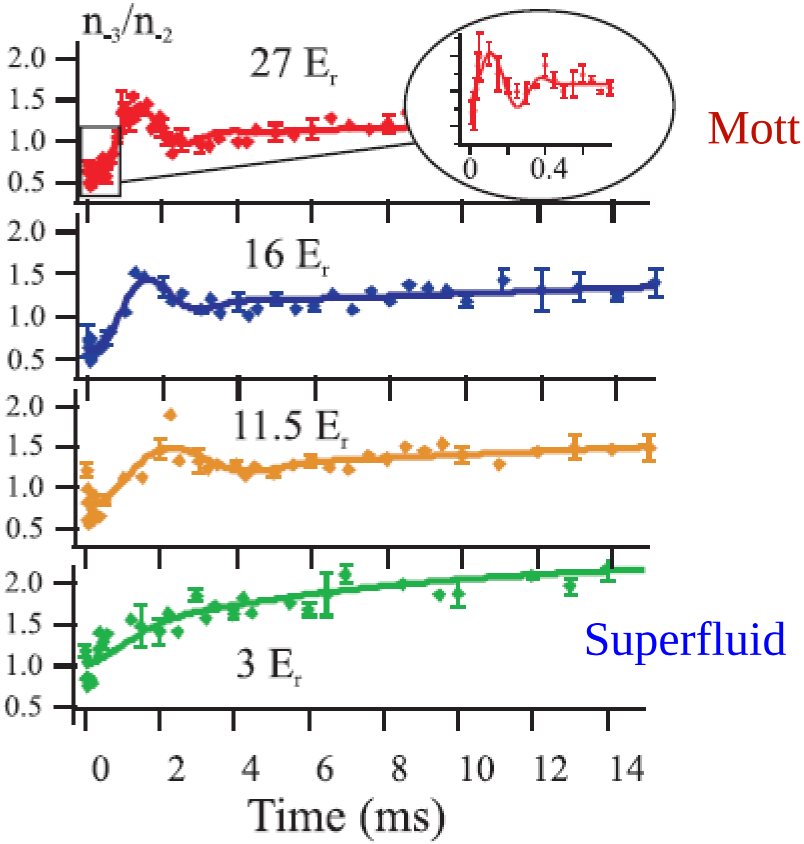
$$\Gamma = \frac{4\pi\hbar^2}{m} n\left(a_6 - a_4\right)$$

Dipolar Exchange (II)

Exact diagonalization is excluded with two atoms per site
(too many configurations for even a few sites)

2- Spin dynamics as a function of lattice depth

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

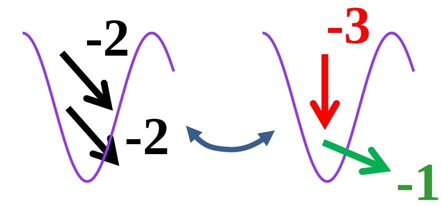
No theoretical model yet
All three exchange mechanisms contribute

A unique and exotic situation!!

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

One interesting regime

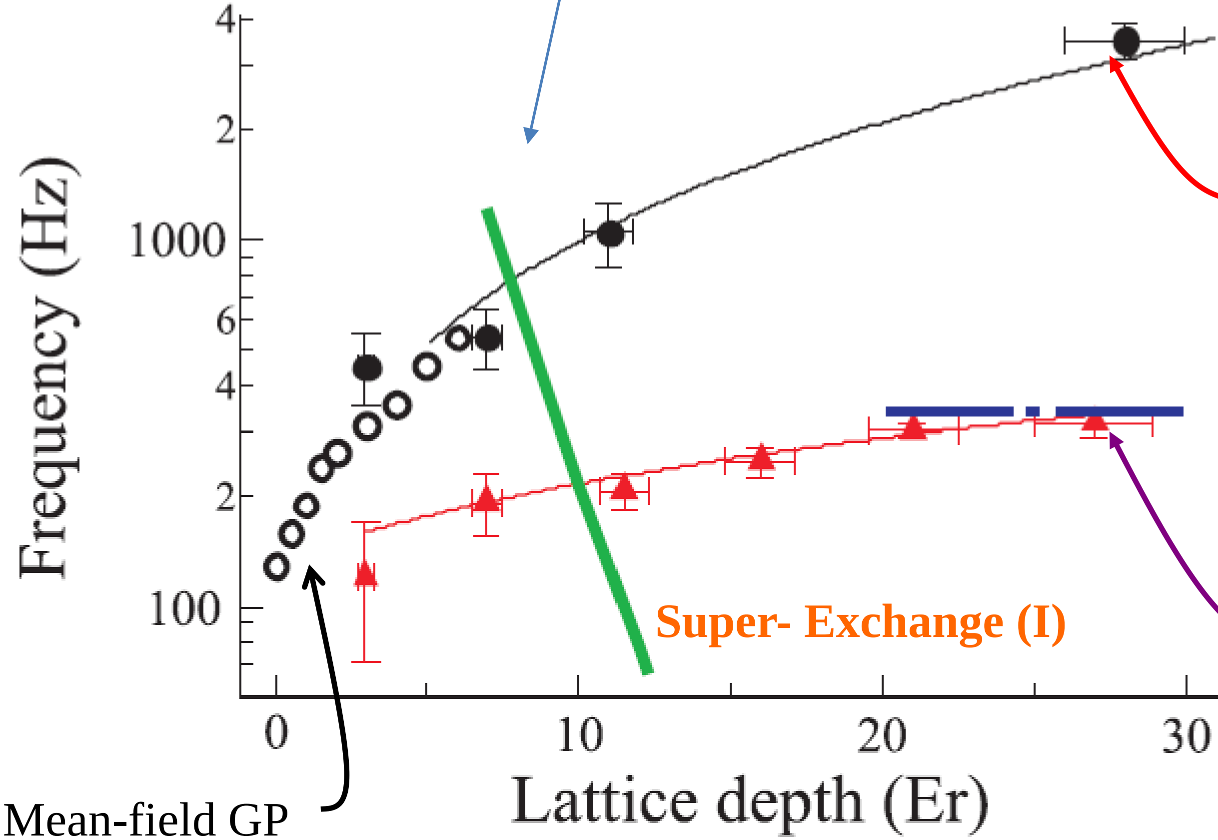
when $V_{dd} \approx \left| \frac{J^2}{U_S} - \frac{J^2}{U_{S+2}} \right|$?



Two-body spin dynamics in isolated lattice sites

$$4\pi \frac{\hbar^2}{m}(a_6 - a_4)\bar{n}$$

Contact exchange (III)



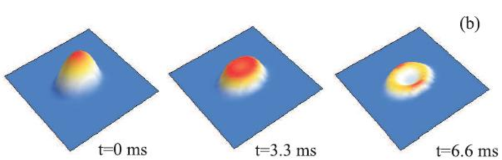
Many-body spin dynamics due to intersite couplings

$$2\pi \sqrt{\sum_{(i,j)} V_{i,j}^2}$$

4th order correction included

Dipolar Exchange (II)

Mean-field GP

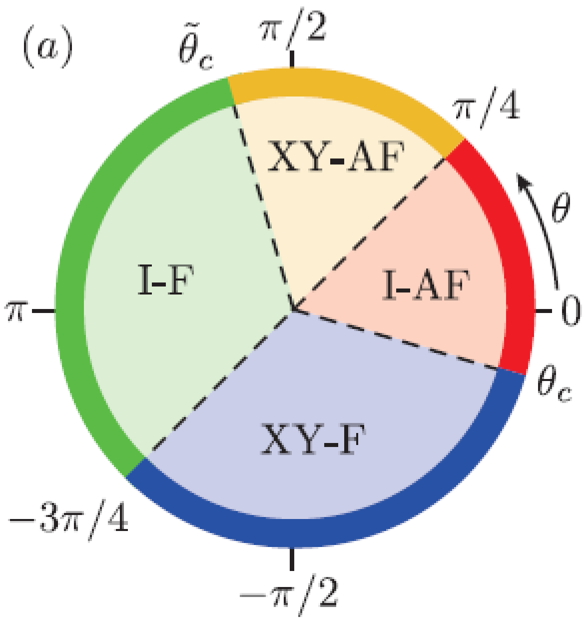


Increasing quantum-ness (?)

Other consequences, due to long range character and anisotropy

Anomalous spin behavior

long range character



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

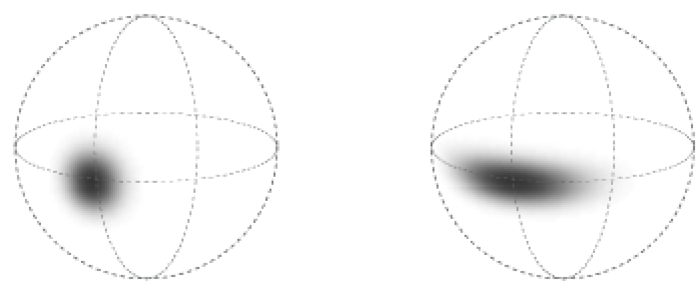
Possibility of long-range ferromagnetic order in 2D (in contrast to Mermin Wagner theorem for short-range interactions)

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

XYZ Hamiltonian
Spin-orbit coupling when magnetization is free (anisotropy)
(Rey, Buchler, Zoller, Karr, Lev…)

Needs to engineer two degenerate states of different magnetization

How correlations develop and spread
(Non-Heisenberg phyics)



(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

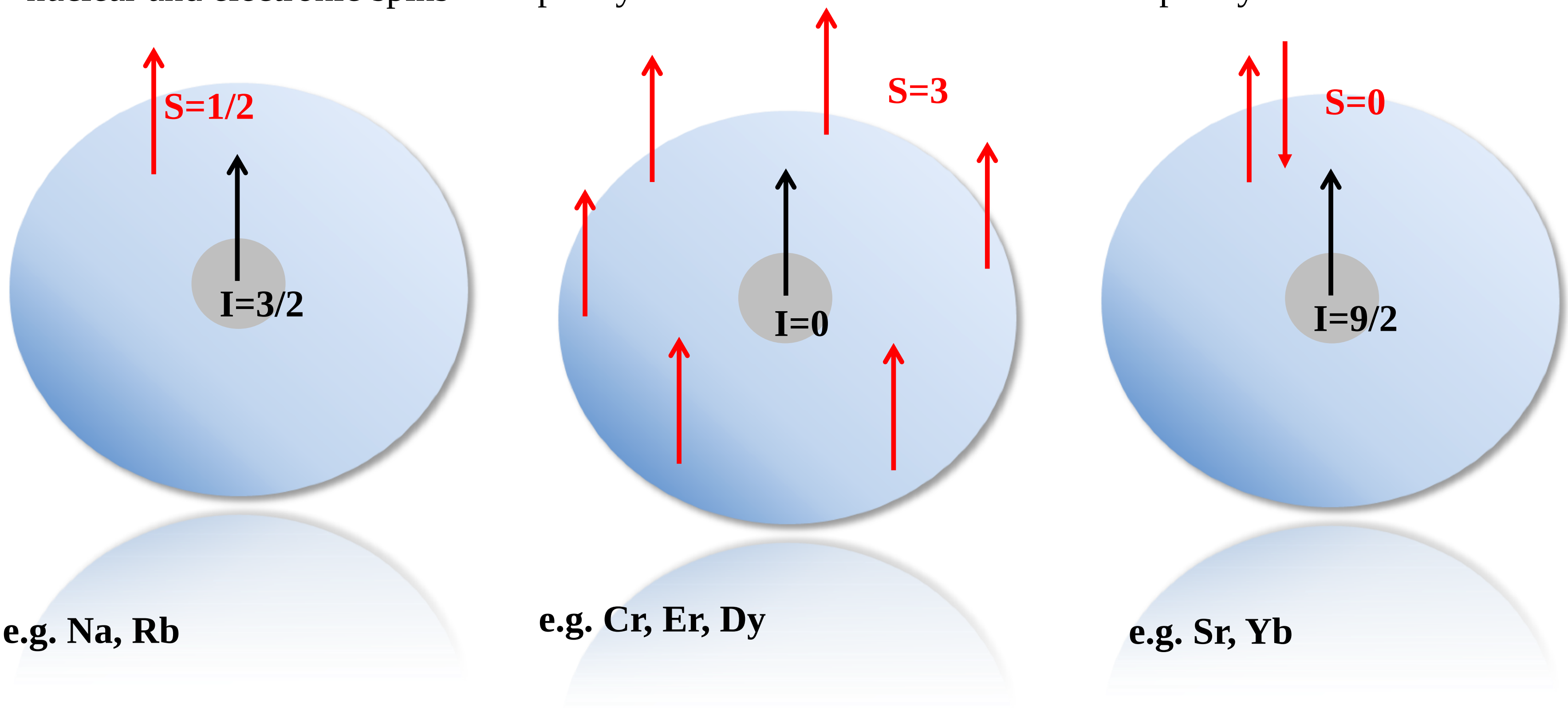
Atoms are composite objects, whose spin can be larger than 1/2

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

Alkali: spin arrises both from nuclear and electronic spins

« magnetic atoms »: spin is purely electronic

Alkaline-earth: spin is purely nuclear



e.g. Na, Rb

e.g. Cr, Er, Dy

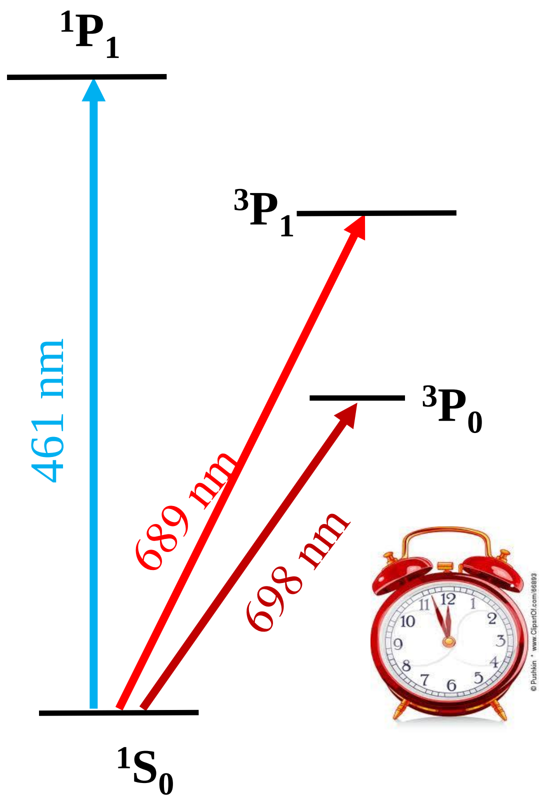
e.g. Sr, Yb

Spin-dependent
contact interactions

Strong dipole-dipole
long-range interaction

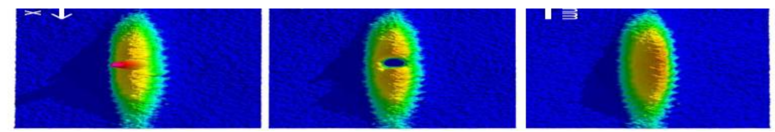
Spin-independent
contact interactions

Introduction to alkaline-earth atoms



Zero electronic spin: no magnetic field sensisivity

Narrow-line laser cooling



Reach degeneracy by simple laser-cooling! (Schreck)

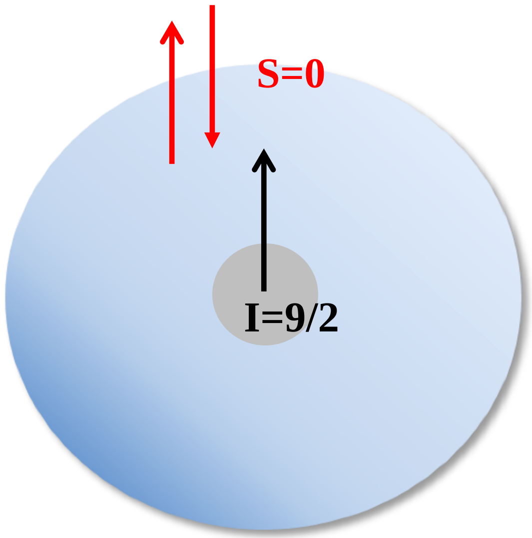
Extremely narrow line

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

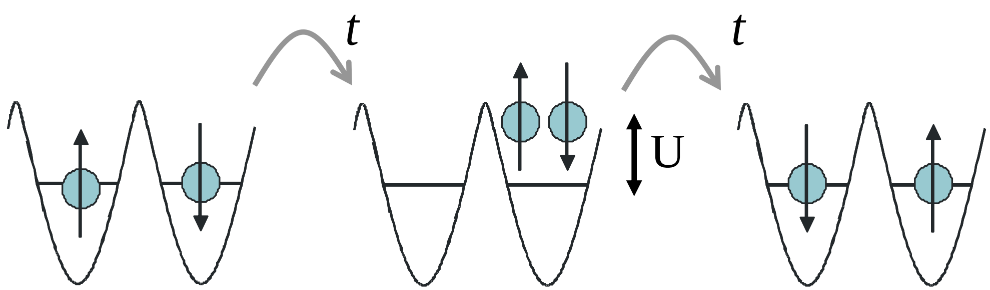
One obvious consequence : non spin-exchange dynamics

- Nothing happens ? Boring ?

- Can prepare arbitrary number of (fixed) « colours »

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

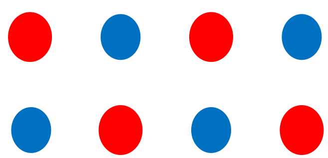
Rule of filling : Two atoms in different states can reduce their energy by tunneling

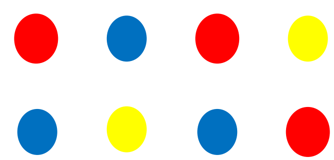


$$\Gamma = -\frac{t^2}{U}$$

Examples:

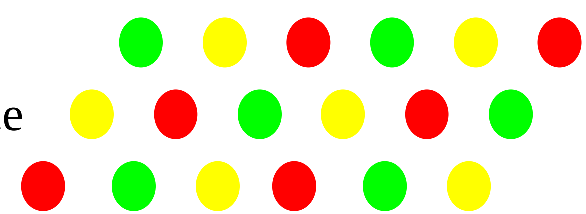
2 colors
Square
Ordered





3 colors
Square
Dis-ordered

3 colors
Triangular lattice
Ordered

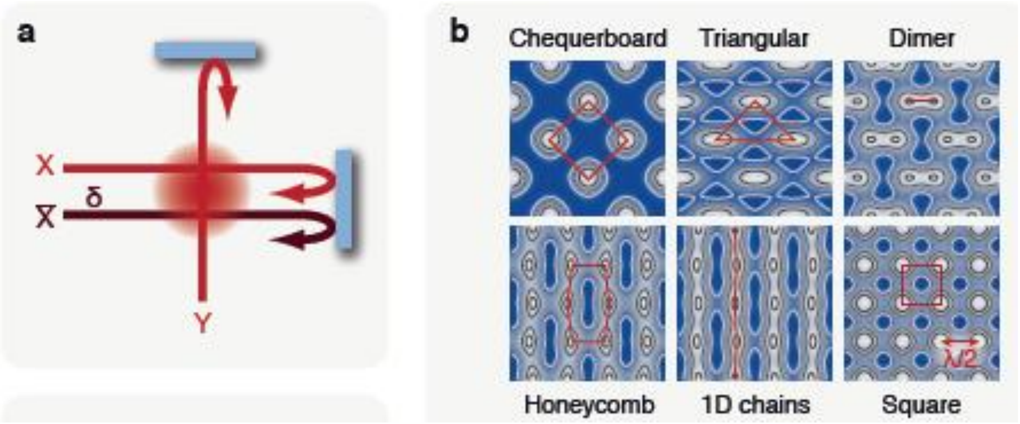


Frederic Mila

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).

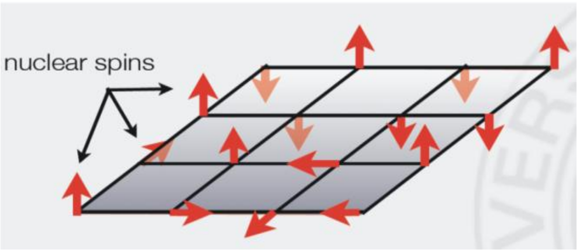
Proposal : interplay between SU(N) magnetism and lattice topology

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



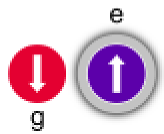
Esslinger

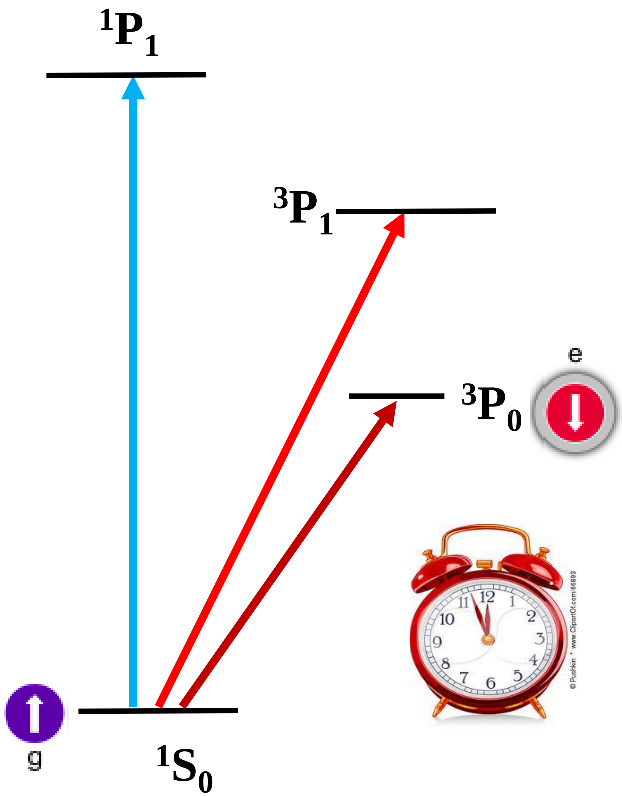
SU(N) symmetry introduces large degeneracies in gound state
Possibilities of spin liquids
(→Effet Hall, frustration, anomalous transport properties…)



Rey, Gorshkov,…

« Orbital » SU(N) magnetism

One prepares a mixture 



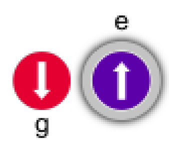
Two possible anti-symmetric states

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

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

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

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

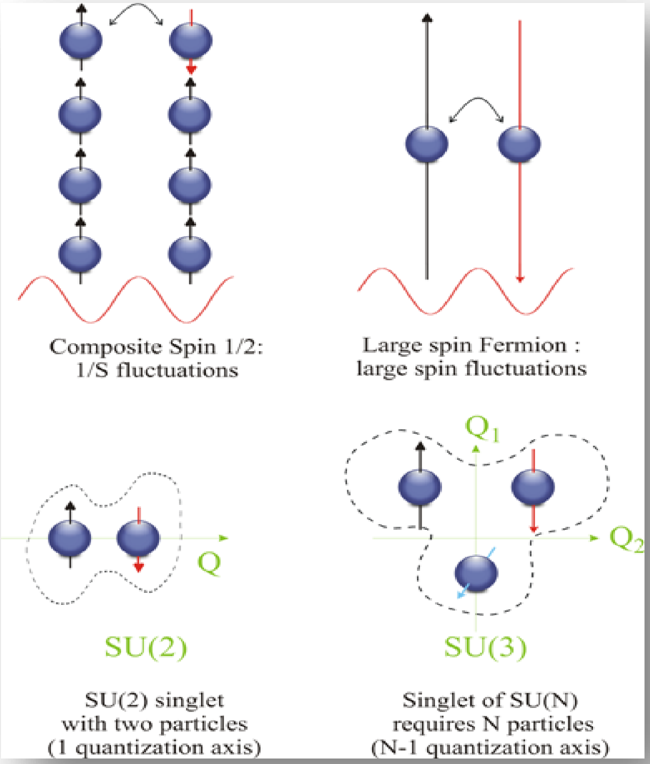


Observation of exchange interactions for a mixture in 1S0 3P0 (Ye, Bloch, Fallani, 2015

Orbital Feshbach resonance (Bloch, Fallani, 2015)

Other fundamental aspects of high spin fermions

Increased spin fluctuations



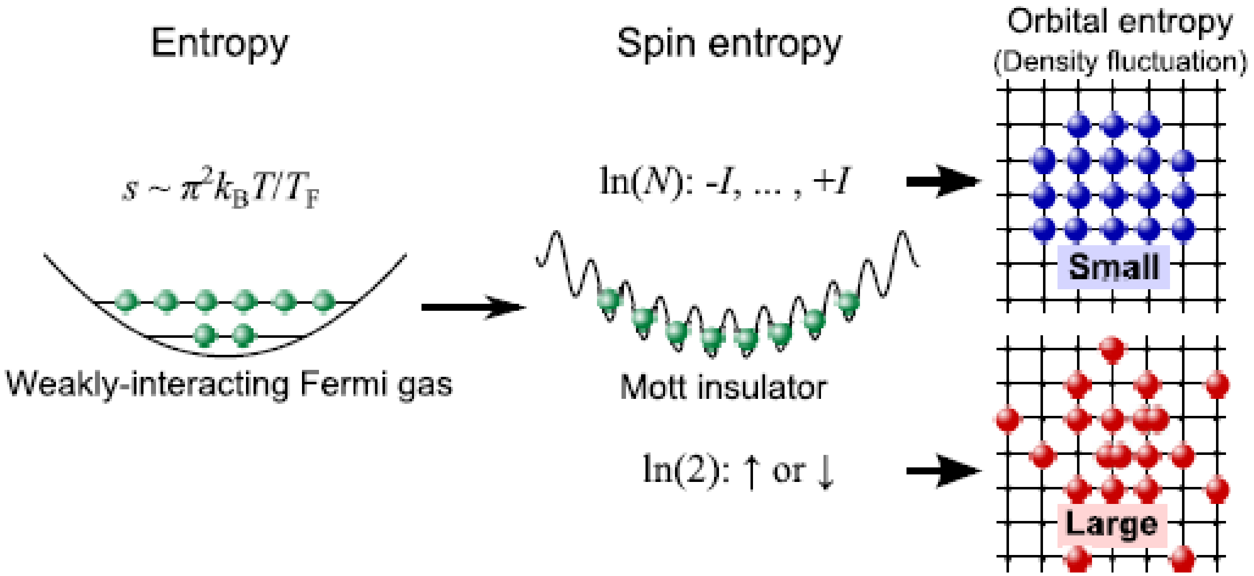
Wu

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

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

Particle clustering; competition between superfluidity and clustering…

Large spin stores entropy!



Takahashi

In addition : correlations may develop as soon as s/N<Log(2F+1)

Alkaline-earth atoms are excellent candidates for exotic quantum magnetism!

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 ?

Thank you

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