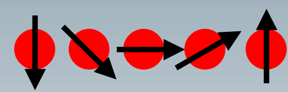
KITP, May 2004 | Quantum Gases Conference

Multi-Component Quantum Gases – Magnetism and a New Realisation of BEC

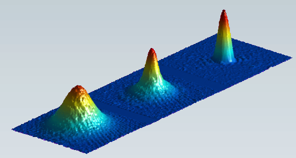
Klaus Sengstock

Spinor quantum gas systems



Ground state properties and dynamics of F=1 and F=2 ^{87}Rb-BEC

Multi-component thermodynamics (condensate melting, magnetization, ‘new‘ path to BEC,...)



Universität Hamburg

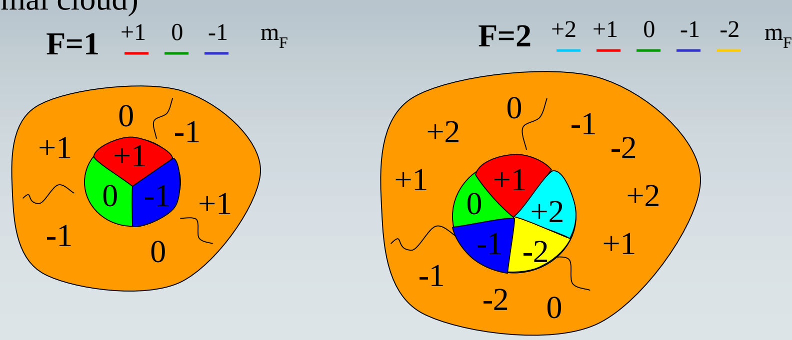
Institut für Laserphysik

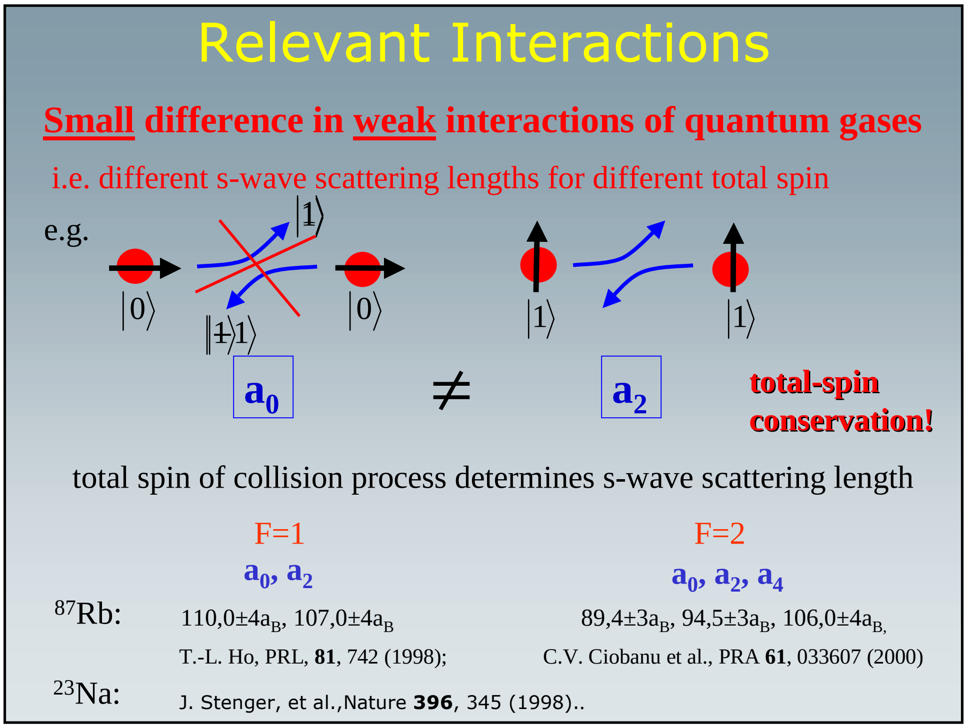
The System

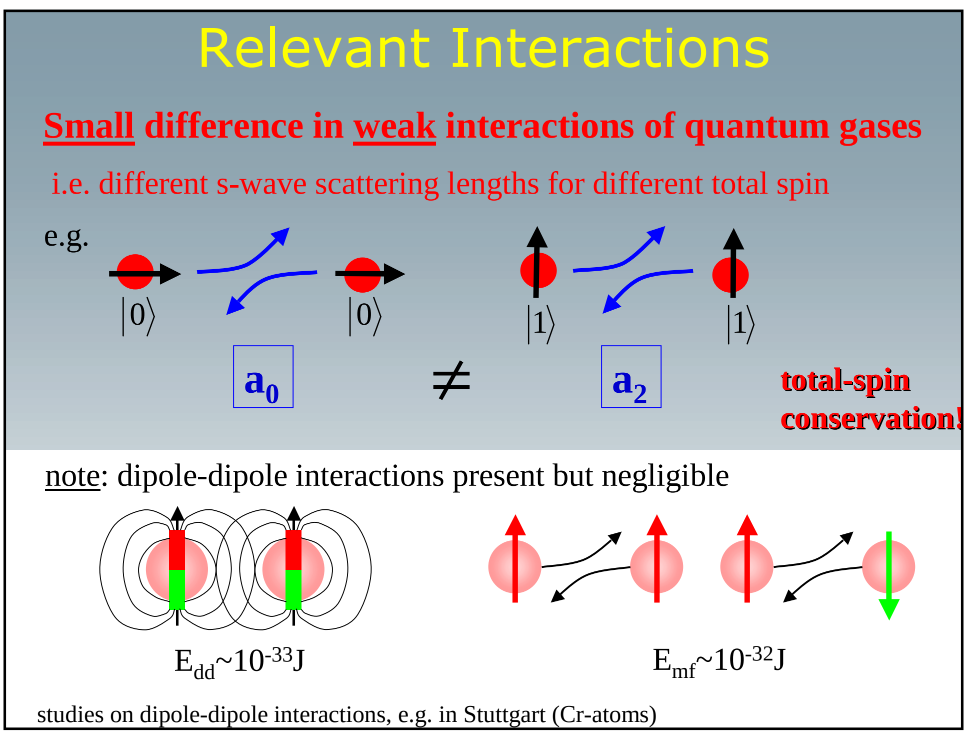
Multi-component spinor-quantum-gases

very rich sytem due to:

- several different interactions (within condensate fraction, within normal cloud and in between)
- exchange of population possible (within condensate fractions and between condensate fraction and normal cloud)




Relevant Interactions
Small difference in weak interactions of quantum gases
i.e. different s-wave scattering lengths for different total spin
e.g.
|0⟩
|0⟩
|1⟩
|-1⟩
|1⟩
|1⟩
a0
≠
a2
total-spin conservation!
total spin of collision process determines s-wave scattering length
F=1
a0, a2
F=2
a0, a2, a4
87Rb:
110,0±4aB, 107,0±4aB
89,4±3aB, 94,5±3aB, 106,0±4aB,
T.-L. Ho, PRL, 81, 742 (1998);
C.V. Ciobanu et al., PRA 61, 033607 (2000)
23Na:
J. Stenger, et al.,Nature 396, 345 (1998)..


Relevant Interactions
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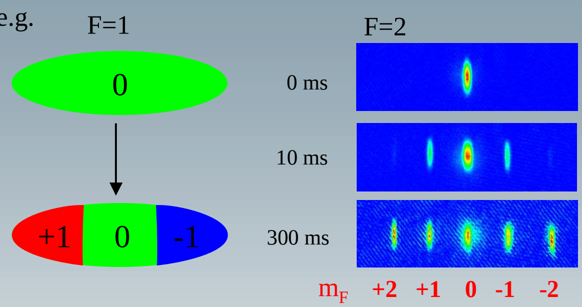
i.e. different s-wave scattering lengths for different total spin
e.g.
|0⟩
|0⟩
|1⟩
|1⟩
a0
≠
a2
total-spin conservation!
note: dipole-dipole interactions present but negligible
Edd~10-33J
Emf~10-32J
studies on dipole-dipole interactions, e.g. in Stuttgart (Cr-atoms)

I. Magnetism in Quantum Gases

System allows studies of spinor condensate dynamics and ground state properties

e.g.



Ho et al. 98
Machida et al. 98
Ketterle et al. 98
Cornell et al. 98
Bigelow et al. 98
Ueda et al. 99
Cirac, Zoller 01
You et al. 02
...
Hamburg group 03
Chapman et al.03

✡ coupled Gross Pitaevskii equations vs.

✡ physics beyond GPE (entanglement, damping,...)

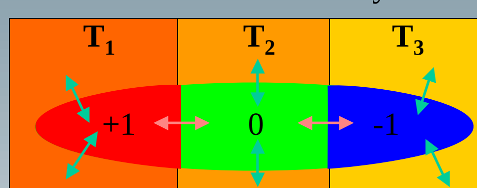
↓

quantum information applications

spinor BEC in optical lattices

II. Multi Component Quantum Gas Thermodynamics

✡ How do different quantum gas components at different T do interact with each other and how do they exchange population?



temperature reservoir and particle reservoir

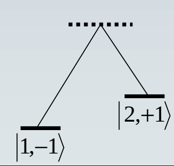
Jila
Hamburg

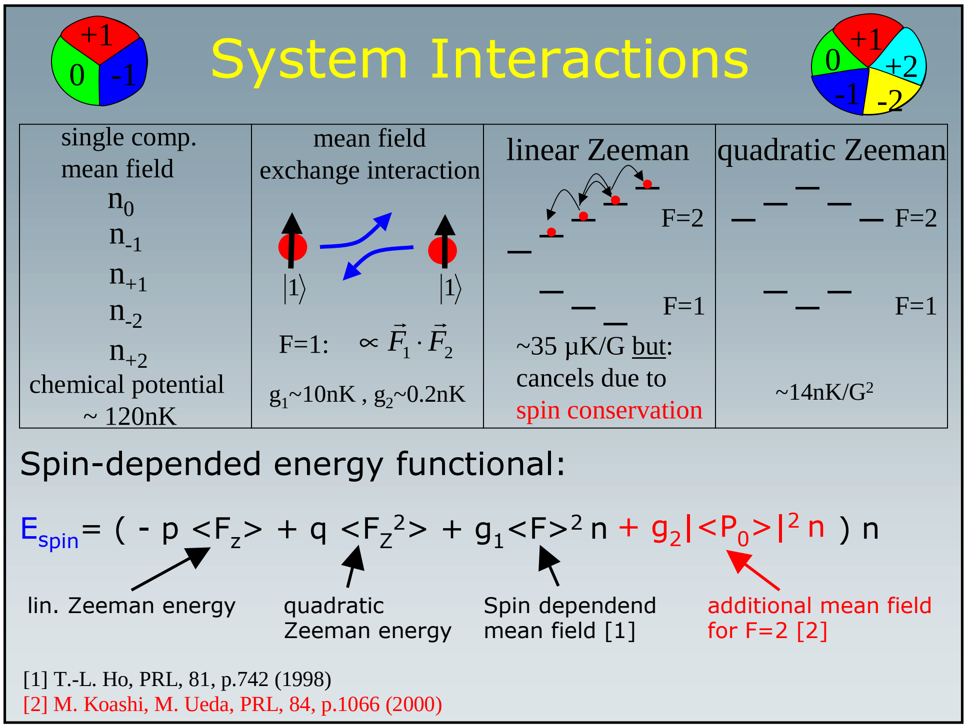
Theory?

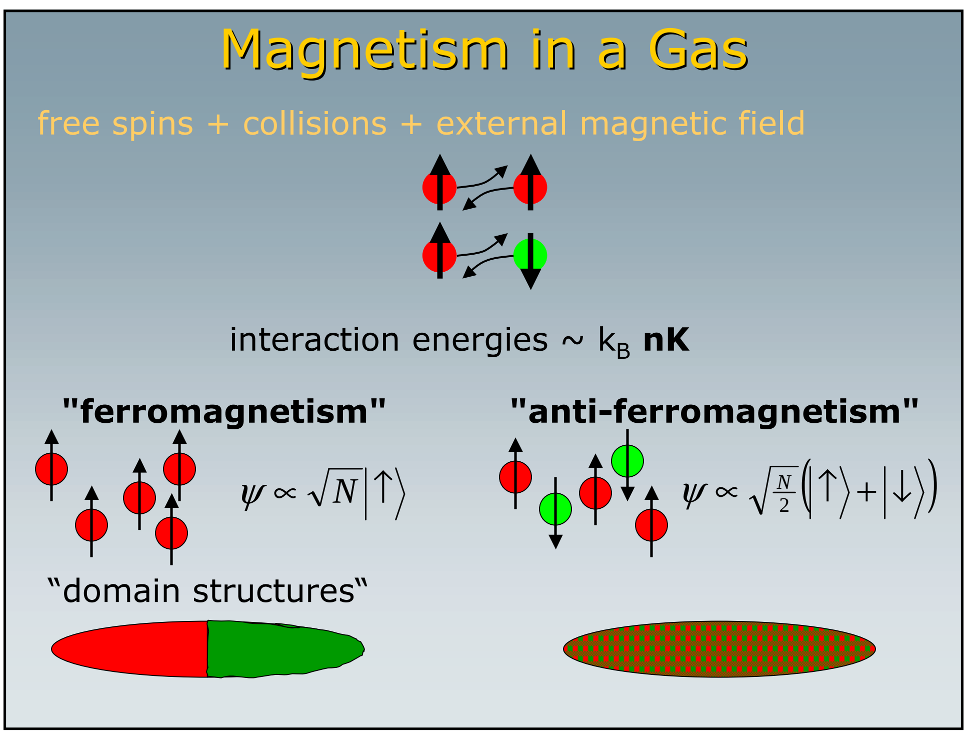
special here, combination of:

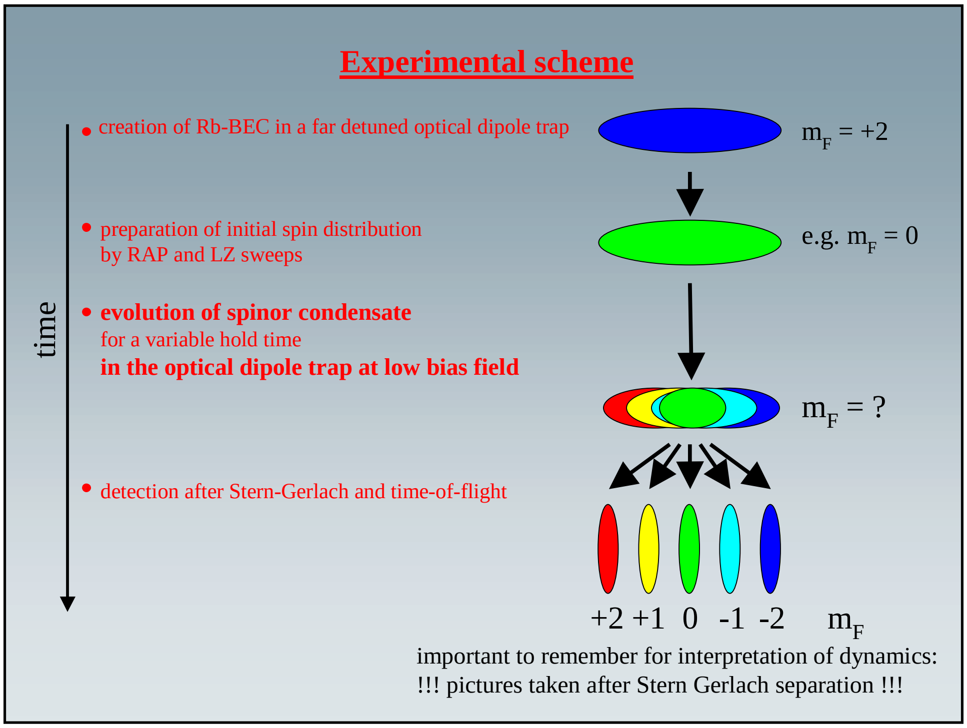
- different time scales for spin dynamics within condensate fraction and thermalization
- allows, **e.g.:**
  - ✡ new path to BEC
  - ✡ condensate melting
  - ✡ temperature driven magnetization !

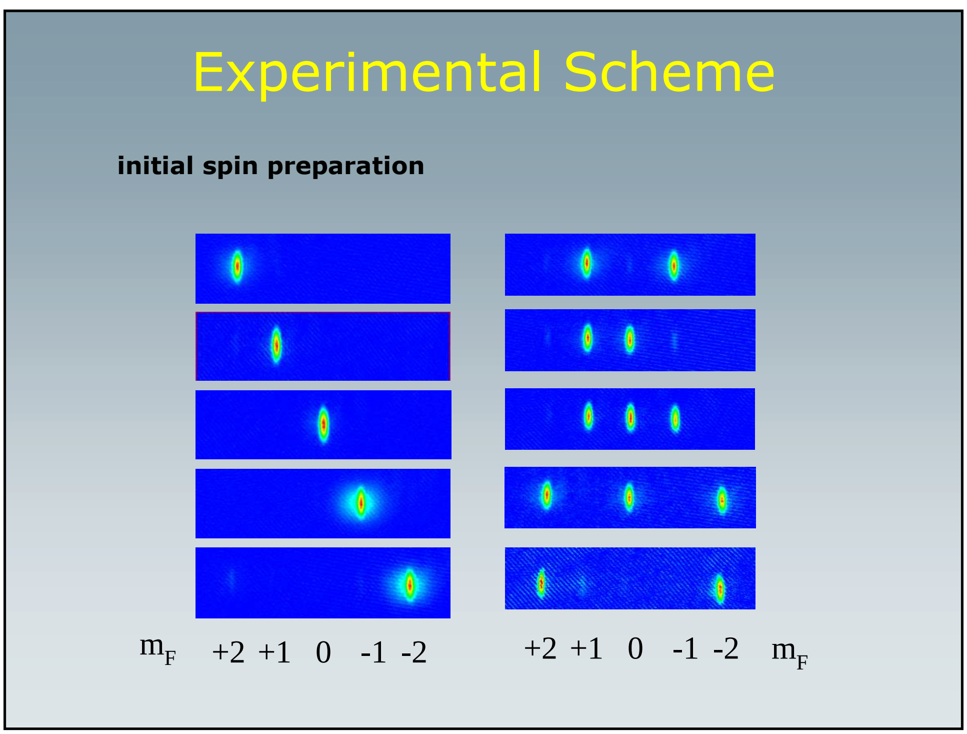
Related system: effective spin-1/2 quantum gas (Cornell et al.)
(no self-driven population transfer)

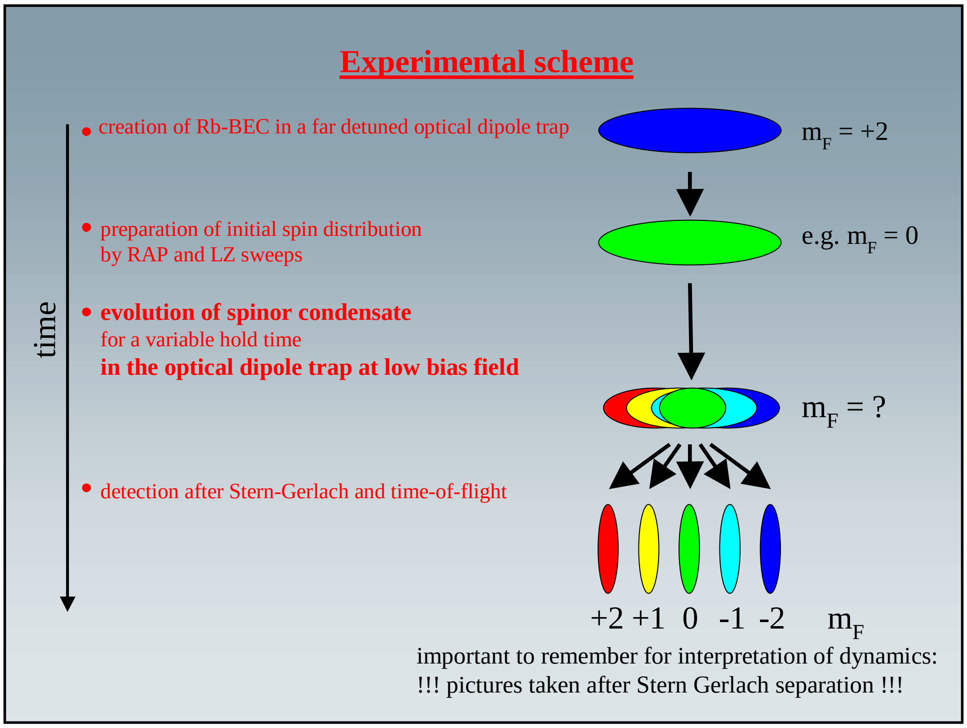



System Interactions
+1
0
-1
+2
-2
single comp. mean field
n_0
n_{-1}
n_{+1}
n_{-2}
n_{+2}
chemical potential ~ 120nK
mean field exchange interaction
$|1\rangle$
$|1\rangle$
F=1: $\propto \vec{F}_1 \cdot \vec{F}_2$
g_1~10nK , g_2~0.2nK
linear Zeeman
F=2
F=1
~35 µK/G but:
cancels due to
spin conservation
quadratic Zeeman
F=2
F=1
~14nK/G²
Spin-depended energy functional:
$E_{spin} = (- p \langle F_z \rangle + q \langle F_z^2 \rangle + g_1 \langle F \rangle^2 n + g_2 |\langle P_0 \rangle|^2 n) n$
lin. Zeeman energy
quadratic Zeeman energy
Spin dependend mean field [1]
additional mean field for F=2 [2]
[1] T.-L. Ho, PRL, 81, p.742 (1998)
[2] M. Koashi, M. Ueda, PRL, 84, p.1066 (2000)


Magnetism in a Gas
free spins + collisions + external magnetic field
interaction energies ~ k_B **nK**
"ferromagnetism"
$\psi \propto \sqrt{N} |\uparrow\rangle$
"anti-ferromagnetism"
$\psi \propto \sqrt{\frac{N}{2}} \left(|\uparrow\rangle + |\downarrow\rangle \right)$
"domain structures"


Experimental scheme
creation of Rb-BEC in a far detuned optical dipole trap
preparation of initial spin distribution by RAP and LZ sweeps
evolution of spinor condensate for a variable hold time in the optical dipole trap at low bias field
detection after Stern-Gerlach and time-of-flight
time
m_F = +2
e.g. m_F = 0
m_F = ?
+2 +1 0 -1 -2 m_F
important to remember for interpretation of dynamics:
!!! pictures taken after Stern Gerlach separation !!!


Experimental Scheme
initial spin preparation
m_F +2 +1 0 -1 -2
+2 +1 0 -1 -2 m_F


Experimental scheme
time
• creation of Rb-BEC in a far detuned optical dipole trap
• preparation of initial spin distribution by RAP and LZ sweeps
• evolution of spinor condensate for a variable hold time in the optical dipole trap at low bias field
• detection after Stern-Gerlach and time-of-flight
$m_F = +2$
e.g. $m_F = 0$
$m_F = ?$
+2 +1 0 -1 -2 m_F
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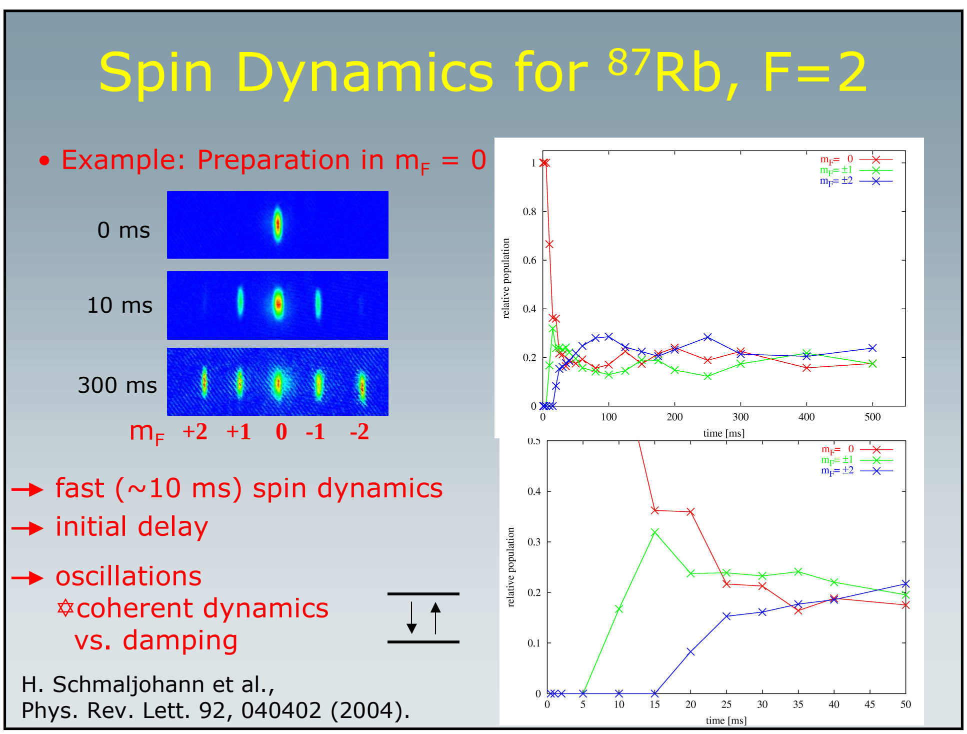

Spin Dynamics for ^{87}Rb, F=2
• Example: Preparation in $m_F = 0$
0 ms
10 ms
300 ms
m_F +2 +1 0 -1 -2
→ fast (~10 ms) spin dynamics
→ initial delay
→ oscillations
✡coherent dynamics
vs. damping
H. Schmaljohann et al.,
Phys. Rev. Lett. 92, 040402 (2004).
relative population
time [ms]
$m_F = 0$
$m_F = \pm 1$
$m_F = \pm 2$

Spin Dynamics - Simulation

- based on coupled GPE (T = 0), homogenous case:

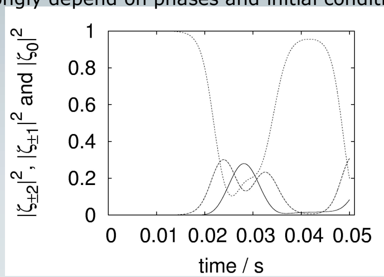
$$\vec{\varphi}(\vec{r},t) = \sqrt{n(\vec{r},t)}e^{i\phi(t)} \cdot \vec{\zeta}(\vec{r},t)$$

$$\begin{aligned} i\hbar\frac{\partial}{\partial t}\sqrt{n(\vec{r},t)}e^{i\phi(t)} &= \left(-\frac{\hbar^2\nabla^2}{2m} + V_{ext.}(\vec{r}) + g_0 n(\vec{r})\right)\sqrt{n(\vec{r},t)}e^{\phi(t)}, \\ i\hbar\frac{\partial}{\partial t}\vec{\zeta}(\vec{r},t) &= \tilde{g}_2 n(\vec{r})\vec{\mathcal{S}}\vec{\zeta}(\vec{r},t)\vec{\zeta}^*(\vec{r},t)\vec{\mathcal{S}}\vec{\zeta}(\vec{r},t) \\ &\quad + \tilde{g}_4 n(\vec{r})\vec{\mathcal{S}}^2\vec{\zeta}(\vec{r},t)\vec{\zeta}^*(\vec{r},t)\vec{\mathcal{S}}^2\vec{\zeta}(\vec{r},t) \\ &\quad - p\mathcal{S}_z\vec{\zeta}(\vec{r},t) + q(\mathcal{S}_z^2\vec{\zeta}(\vec{r},t) - 4). \end{aligned}$$

$$\begin{aligned} i\hbar\frac{\partial}{\partial t}\zeta_{+1} &= g_2 n\,\zeta_{-1}^*\zeta_0^2 - p\zeta_{+1} - 3q\zeta_{+1}, \\ i\hbar\frac{\partial}{\partial t}\zeta_0 &= 2g_2 n\,\zeta_0^*\zeta_1\zeta_{-1} - 4q\zeta_0, \\ i\hbar\frac{\partial}{\partial t}\zeta_{-1} &= g_2 n\,\zeta_{+1}^*\zeta_0^2 + p\zeta_{-1} - 3q\zeta_{-1}. \end{aligned}$$

delayed build up, oscillations,...
strongly depend on phases and initial conditions

F=2:



small seed in +/-1 and +/-2 comp.: 10^{-4}

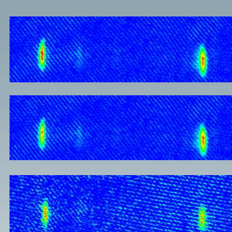
Ground state properties

antiferromagnetic ground state is stable for Rb F = 2

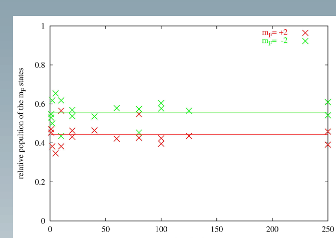
0 ms

10 ms

300 ms



m_F +2 +1 0 -1 -2

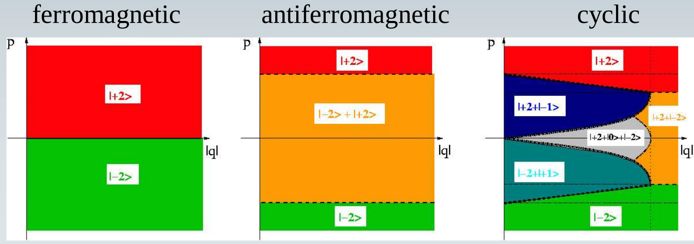


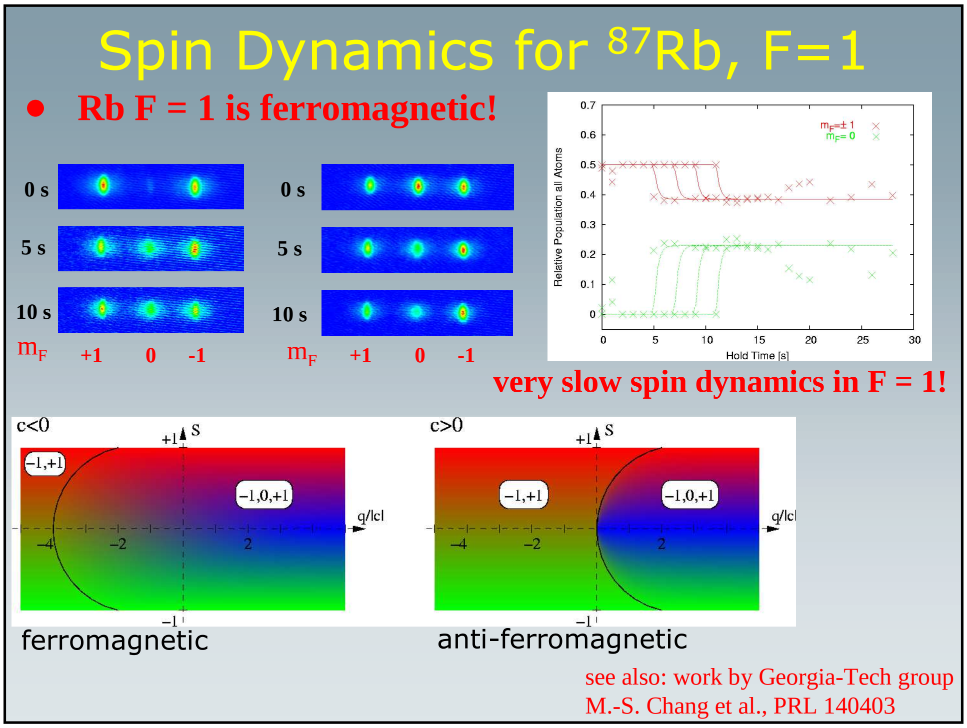
and is superposed in trap!

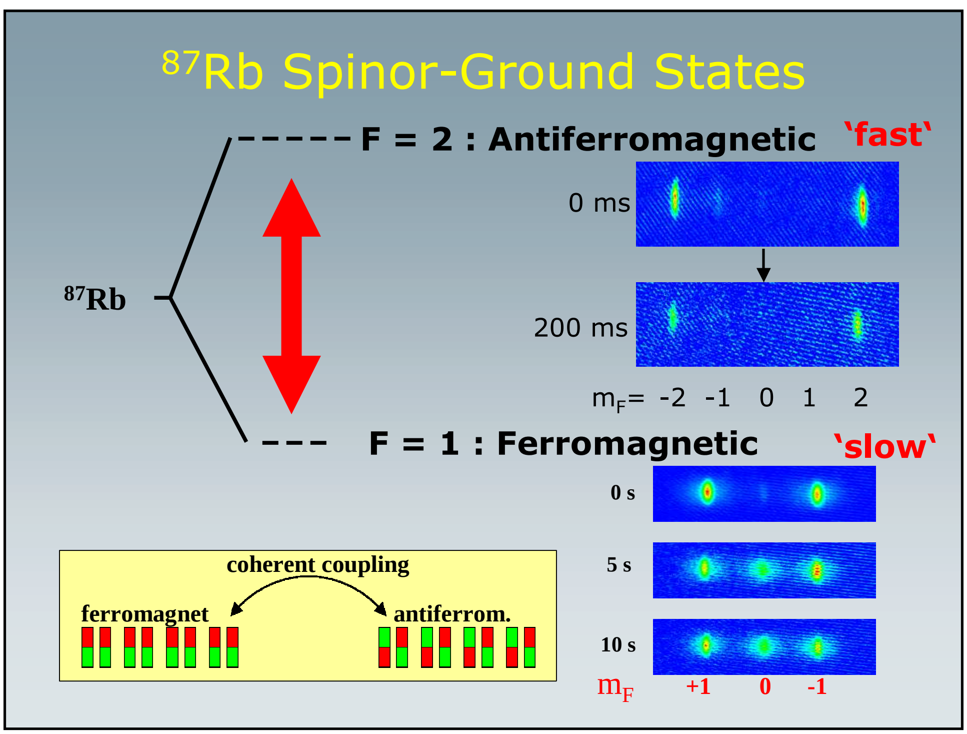
^{87}Rb F = 2 is antiferromagnetic

ferromagnetic | antiferromagnetic | cyclic

F=2 phase diagrams
our calculations



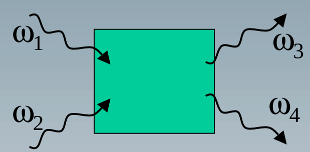

Spin Dynamics for 87Rb, F=1
Rb F = 1 is ferromagnetic!
0 s
5 s
10 s
mF +1 0 -1
0 s
5 s
10 s
mF +1 0 -1
Relative Population all Atoms
Hold Time [s]
mF=± 1
mF= 0
very slow spin dynamics in F = 1!
c<0
c>0
S
q/|c|
−1,+1
−1,0,+1
ferromagnetic
anti-ferromagnetic
see also: work by Georgia-Tech group
M.-S. Chang et al., PRL 140403


87Rb Spinor-Ground States
F = 2 : Antiferromagnetic
'fast'
0 ms
200 ms
mF= -2 -1 0 1 2
87Rb
F = 1 : Ferromagnetic
'slow'
0 s
5 s
10 s
mF +1 0 -1
coherent coupling
ferromagnet
antiferrom.

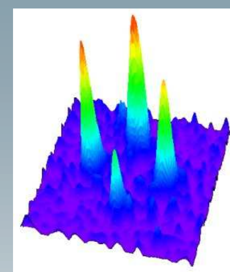
Quantum Gas Four-wave-mixing

quantum optics viewpoint ✡ four-wave-mixing

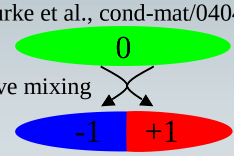
optics:



for BEC
(Phillips et al.):

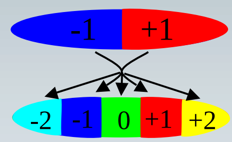


spinor condensates
(J. P. Burke et al., cond-mat/0404499):



✡ fully equivalent description
✡ to populate empty modes:
- seed
- quantum fluctuations

F=2: even more complex



multi mode coupling competing four wave mixing channels

NSE`s:

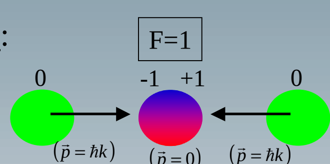
$$i\hbar\frac{\partial}{\partial t}\zeta_{+1} = g_2 n\,\zeta_{-1}^*\zeta_0^2 - p\zeta_{+1} - 3q\zeta_{+1}\,,$$
$$i\hbar\frac{\partial}{\partial t}\zeta_0 = 2g_2 n\,\zeta_0^*\zeta_1\zeta_{-1} - 4q\zeta_0\,,$$
$$i\hbar\frac{\partial}{\partial t}\zeta_{-1} = g_2 n\,\zeta_{+1}^*\zeta_0^2 + p\zeta_{-1} - 3q\zeta_{-1}\,.$$

Quantum Gas Four-wave-mixing

- **adding kinetic energy plus magnetic fields:**

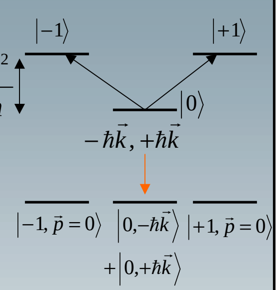
→ additional processes possible

e.g.:

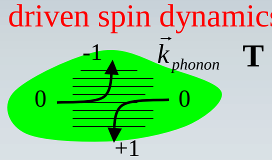


FWM into zero momentum states

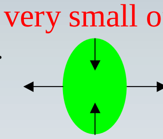
quadratic Zeeman energy $\hat{=} \frac{\hbar^2 k^2}{2m}$



→ phonon driven spin dynamics ??! for very small offset B-field



e.g.

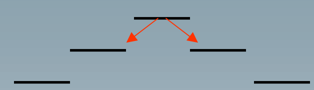


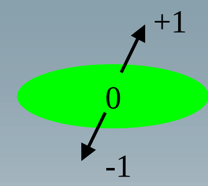
quadrupole mode coupling to spin conversion

→ coupling of spinor components and finite T excitations ?

Quantum Gas Four-wave-mixing

F=2: the other way round...





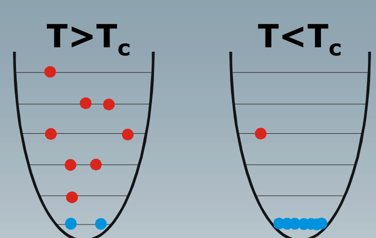
potential energy ✡ kinetic energy

→ four wave mixing for $k_1=k_2=0$! (what we observe!)

→ no grating !?

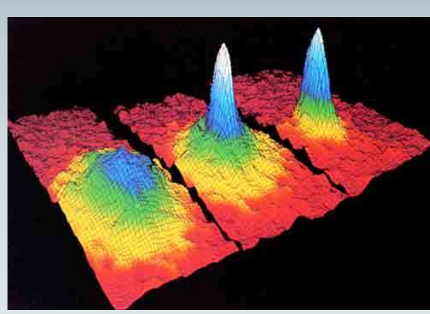
→ entanglement source

BEC Phase Transition

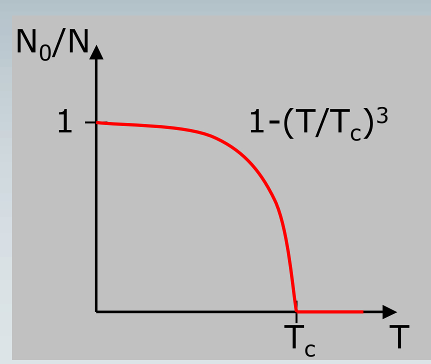


Condition for BEC:

$$n_0 \Lambda_{dB}^3 (T_c) = 2.612...$$

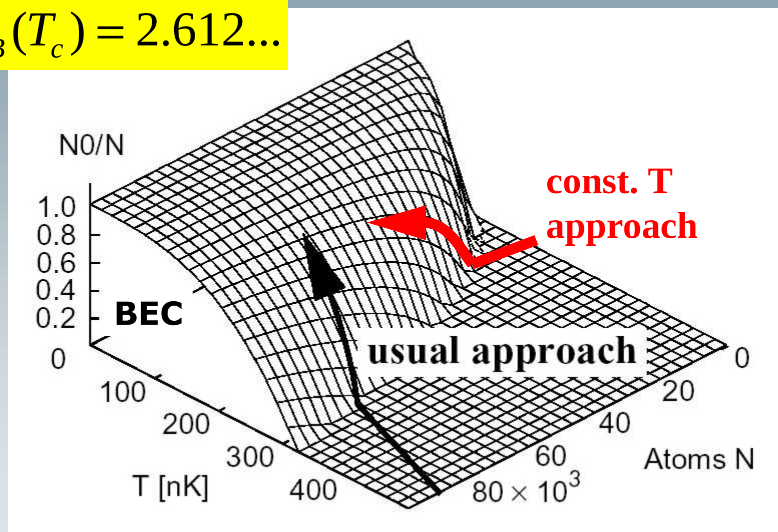


JILA 1995

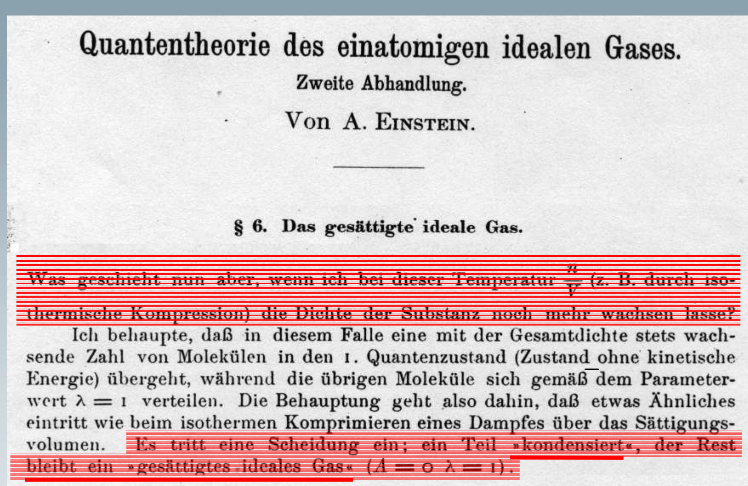


BEC – “new“ aspects

$$n_0 \Lambda_{dB}^3 (T_c) = 2.612...$$



BEC – “new“ aspects



Quantentheorie des einatomigen idealen Gases.

Zweite Abhandlung.

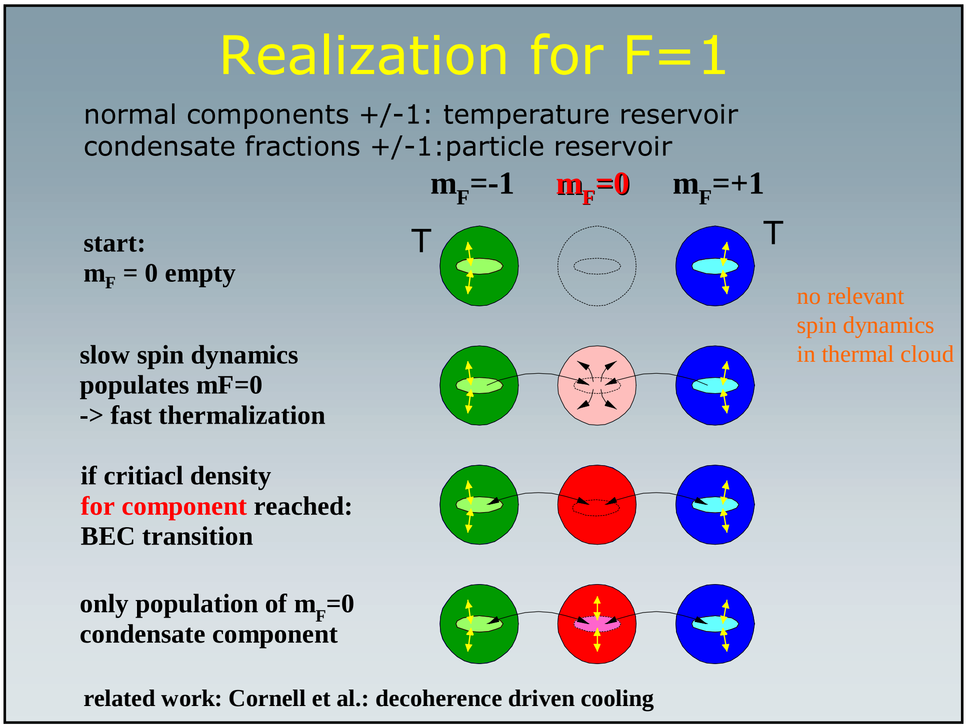
Von A. Einstein.

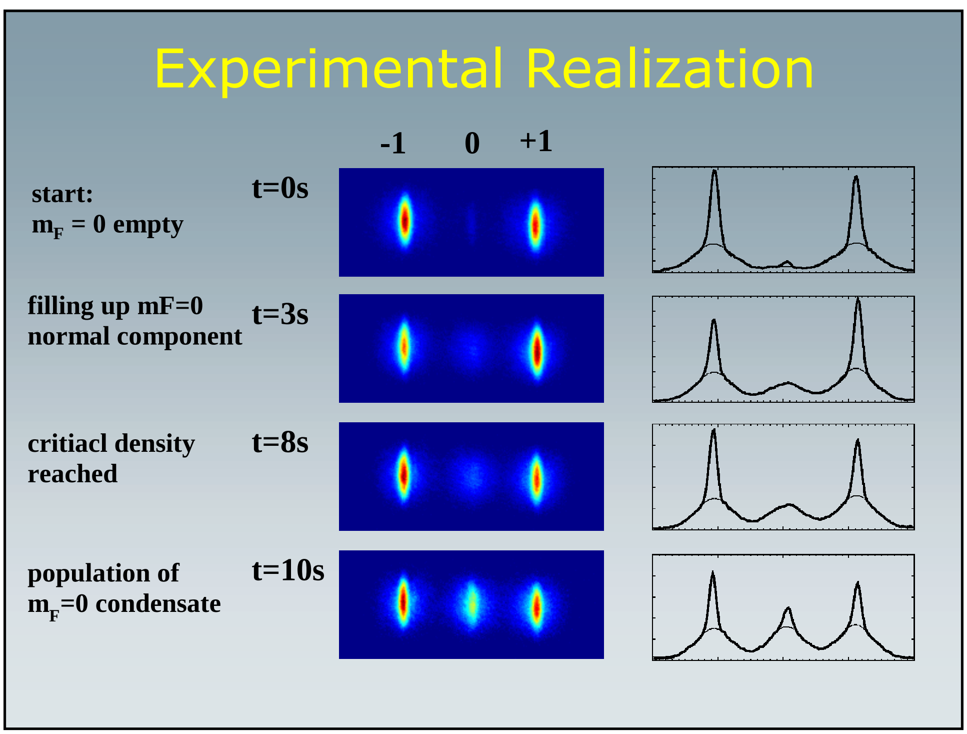
§ 6. Das gesättigte ideale Gas.

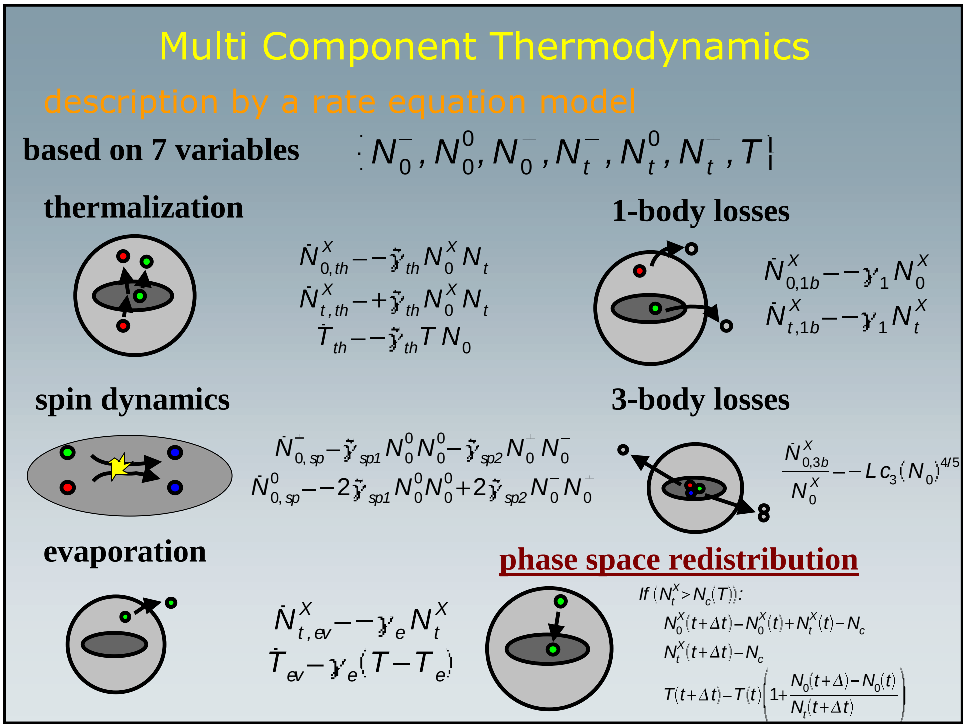
Was geschieht nun aber, wenn ich bei dieser Temperatur $\frac{n}{V}$ (z. B. durch isothermische Kompression) die Dichte der Substanz noch mehr wachsen lasse?

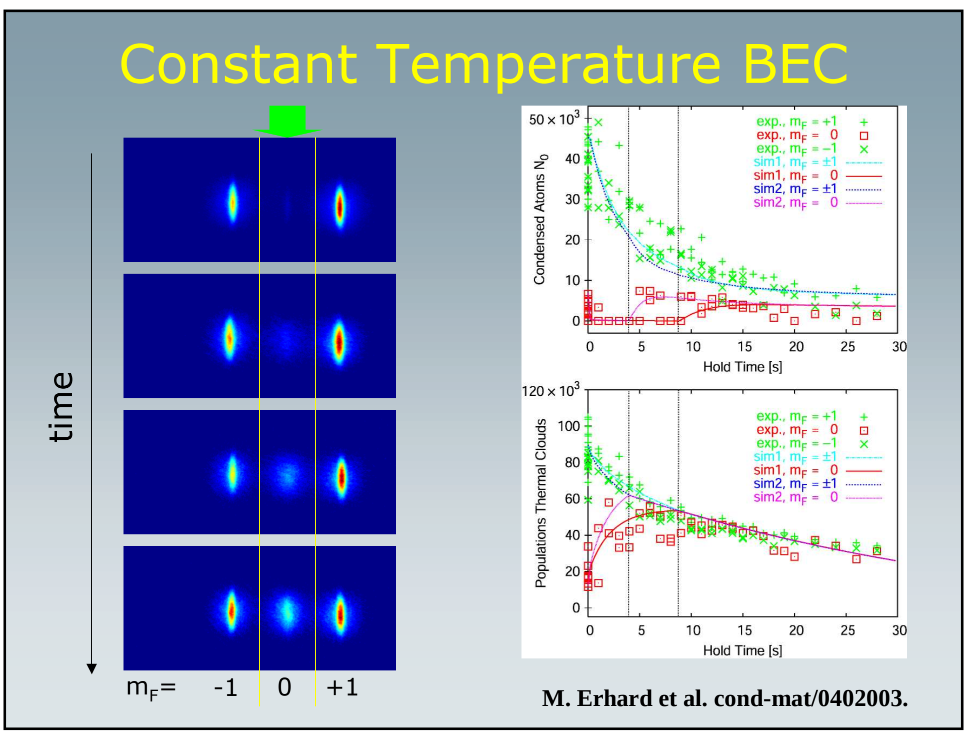
Ich behaupte, daß in diesem Falle eine mit der Gesamtdichte stets wachsende Zahl von Molekülen in den 1. Quantenzustand (Zustand ohne kinetische Energie) übergeht, während die übrigen Moleküle sich gemäß dem Parameterwert $\lambda = 1$ verteilen. Die Behauptung geht also dahin, daß etwas Ähnliches eintritt wie beim isothermen Komprimieren eines Dampfes über das Sättigungsvolumen. Es tritt eine Scheidung ein; ein Teil »kondensiert«, der Rest bleibt ein »gesättigtes ideales Gas« ($A = 0$ $\lambda = 1$).

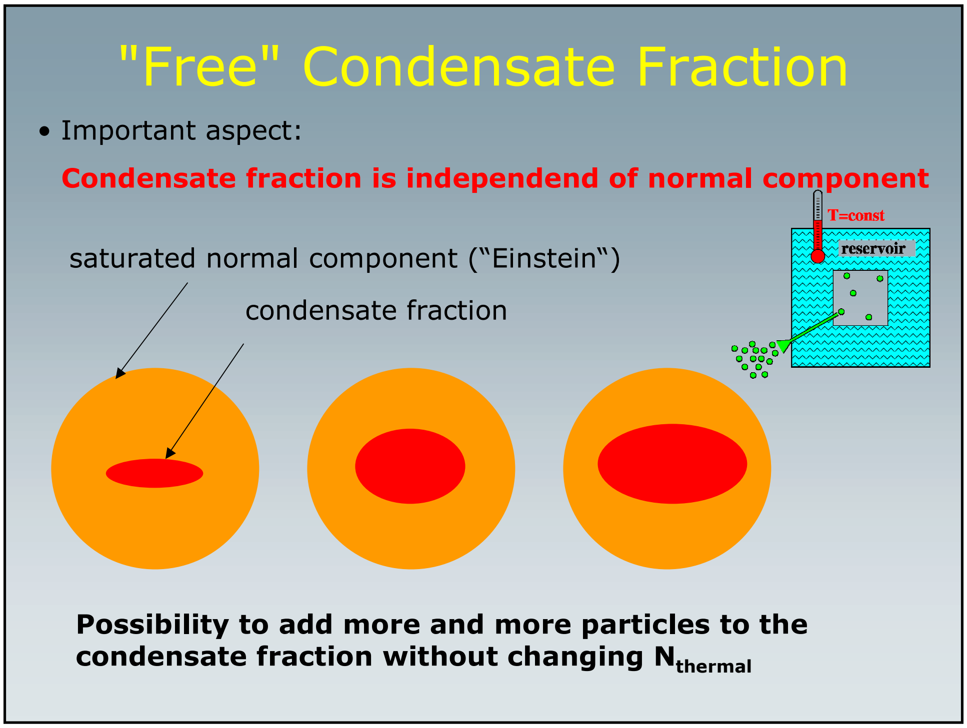
A. Einstein,
Sitzungsber. Preuss. Akad. Wiss., 3, **1925**

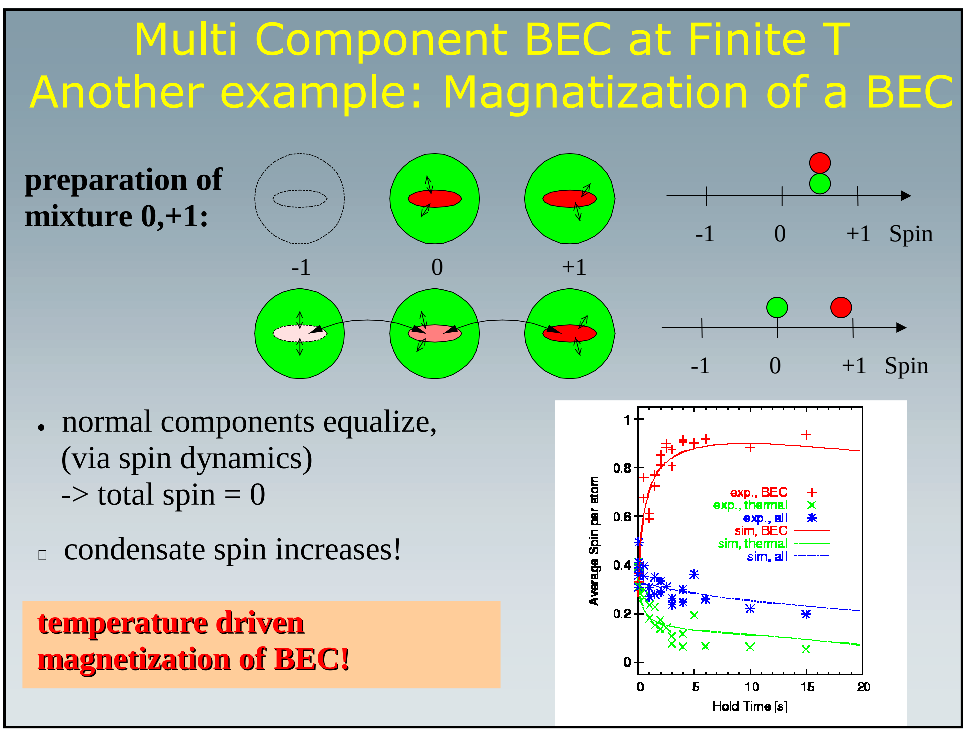

Realization for F=1
normal components +/-1: temperature reservoir
condensate fractions +/-1:particle reservoir
m_F=-1 m_F=0 m_F=+1
start:
m_F = 0 empty
T
T
no relevant spin dynamics in thermal cloud
slow spin dynamics
populates mF=0
-> fast thermalization
if critiacl density
for component reached:
BEC transition
only population of m_F=0
condensate component
related work: Cornell et al.: decoherence driven cooling


Experimental Realization
-1 0 +1
start:
m_F = 0 empty
t=0s
filling up mF=0
normal component
t=3s
critiacl density
reached
t=8s
population of
m_F=0 condensate
t=10s


Multi Component Thermodynamics
description by a rate equation model
based on 7 variables
thermalization
1-body losses
spin dynamics
3-body losses
evaporation
phase space redistribution

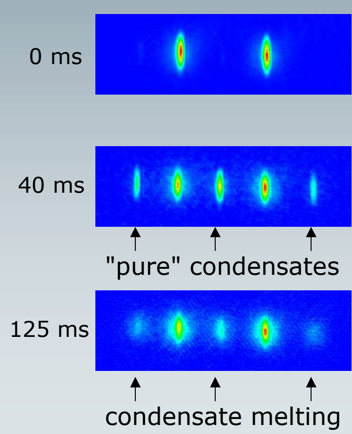

Constant Temperature BEC
time
mF= -1 0 +1
exp., mF = +1
exp., mF = 0
exp., mF = −1
sim1, mF = ±1
sim1, mF = 0
sim2, mF = ±1
sim2, mF = 0
Condensed Atoms N0
Hold Time [s]
Populations Thermal Clouds
M. Erhard et al. cond-mat/0402003.

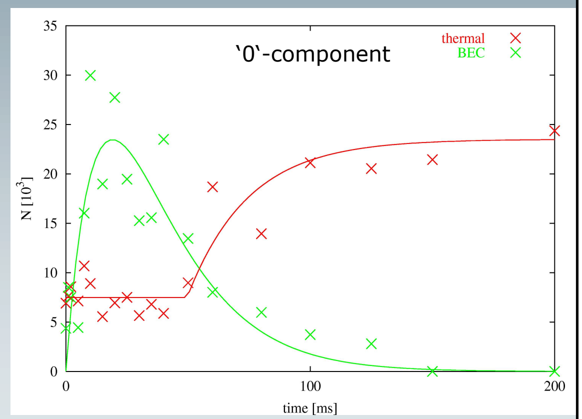

"Free" Condensate Fraction
• Important aspect:
Condensate fraction is independend of normal component
T=const
reservoir
saturated normal component ("Einstein")
condensate fraction
Possibility to add more and more particles to the condensate fraction without changing $N_{thermal}$


Multi Component BEC at Finite T
Another example: Magnatization of a BEC
preparation of mixture 0,+1:
-1
0
+1
-1 0 +1 Spin
-1 0 +1 Spin
• normal components equalize, (via spin dynamics) -> total spin = 0
condensate spin increases!
temperature driven magnetization of BEC!
Average Spin per atom
Hold Time [s]
exp., BEC
exp., thermal
exp., all
sim, BEC
sim, thermal
sim, all

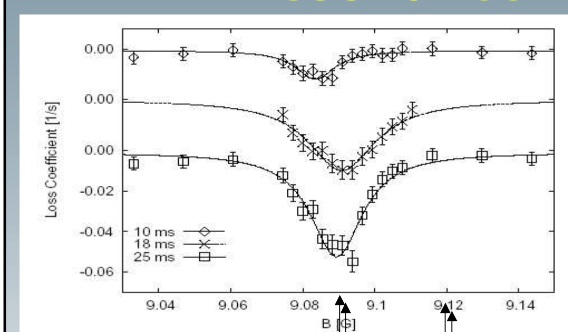
Realization of Condensate Melting

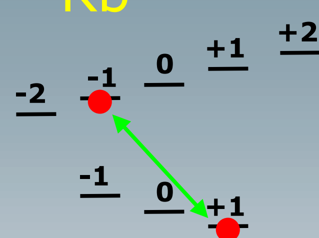
^{87}Rb offers both regimes, condensate melting in F=2:
Fast spin dynamics, slow thermalization





Mixed Hyperfine State Feshbach Resonance in ^{87}Rb





offers further opportunities for manipulation of 87Rb spin mixtures and entanglement

1.) theoretical prediction
(E. van Kempen et al. PRL 88, 093201 (2002))

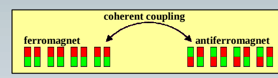
2.) experiment, this work
M. Erhard et al.,
PRA 69, 032705 (2004)
(9.09 +/- 0.01 G)

3.) experiment, München
A. Widera et al., PRL92, 160406 (2004)
(9.121 +/- 0.005 G)

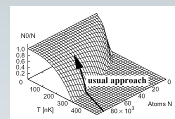
4.) theoretical calculation
Tiemann, priv. com.

Multi-Component BEC

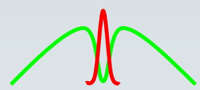
- Magnetic properties of spinor condensates
  H. Schmaljohann et al. **Phys. Rev. Lett. 92, 040402 (2004)**
  J. Mod. Opt.,in press(2004),
  Laser Phys.,in press (2004)
- Tunability by mixed hyperfine state Feshbach resonance
  M. Erhard et al. **PRA 69,032705 (2004)**
- Text book quantum gas thermodynamics
  M. Erhard et al. **cond-mat/0402003.**



Advanced studies on spin-dynamics
  - coupling ferro- and antiferromagnetic states
  - **investigation of coherence and entanglement**
  - **physics beyond 'Gross-Pitaevskii equation'**



- Playing text-book thermodynamics
  - exploration of new regimes
- Filled Spinor Solitons
- **Spinor BEC in optical lattices**



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Marlon Nakat

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Anika Vogel

Q. Gu - Theory

V. M. Baev - Fibre lasers

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Oliver Back
Gerald Rapior
Ortwin Hellmig

Staff

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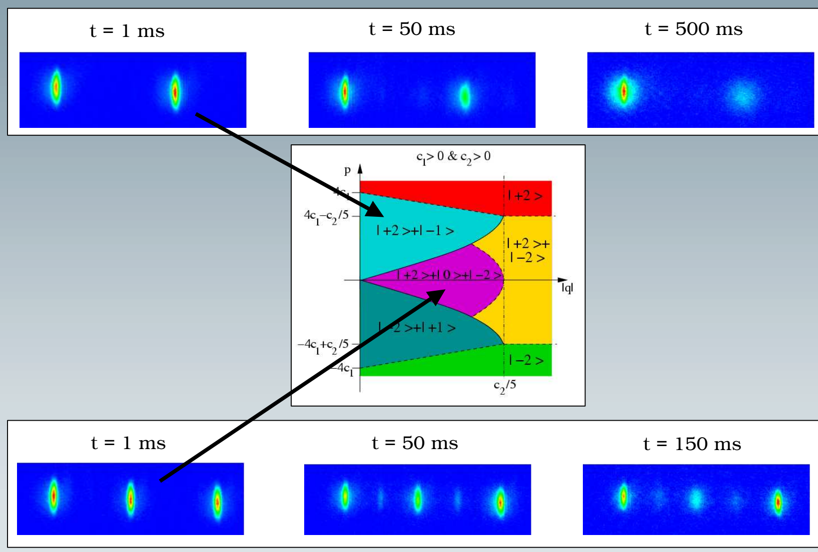
Dieter Barloesius
Reinhard Mielck

The nice city of Hamburg...

new institute building at Hamburg (DESY campus) open for visits!!

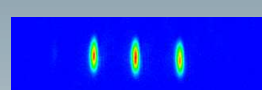
Metastable States



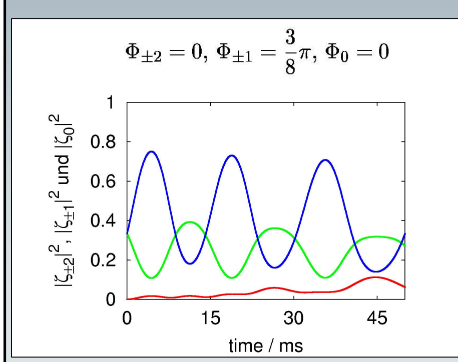
Spin Dynamics – Influence of Phase

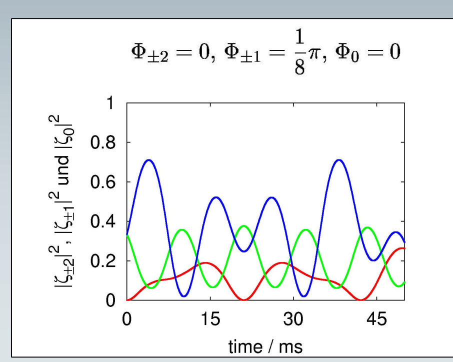
relative phases of spin components important for dynamics

e.g.: preparation of F=2, m_F=+1, 0, -1



simulations:

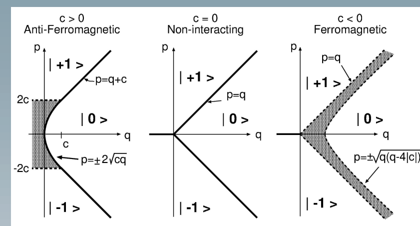




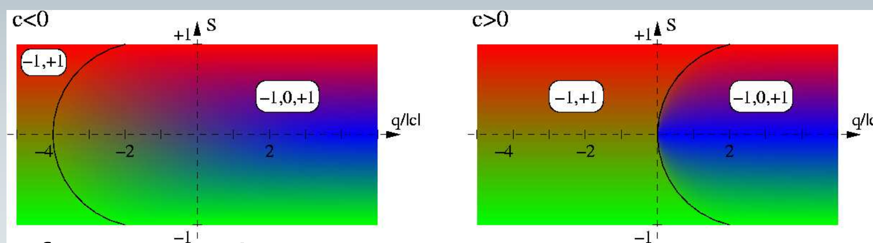
Magnetic Ground States

- **F=1**

representation as function of total spin (s) and offset-magnetic field (q).



J. Stenger, et al., Nature **396**, 345 (1998).



ferromagnetic

anti-ferromagnetic

Spin Dynamics for ^{87}Rb, F=2

initially prepared m_F states	initial total spin	initial channels into m_F state G $[10^{-13}\mathrm{cm}^3\mathrm{s}^{-1}]$	finally populated m_F states
$\|0\rangle$	0	$\rightarrow \|\pm1\rangle \approx 21.0$	equipartition
$\|+1\rangle + \|-1\rangle$	0	$\rightarrow \|0\rangle \approx 26.9$ $\rightarrow \|\pm2\rangle \approx 4.6$	equipartition
$\|+1\rangle + \|0\rangle + \|-1\rangle$	0	$\rightarrow \|\pm2\rangle \approx 5.0$	equipartition
$\|+2\rangle + \|-2\rangle$	0	-	$\|+2\rangle + \|-2\rangle$
$\|+2\rangle + \|0\rangle + \|-2\rangle$	0	$\rightarrow \|\pm1\rangle < 0.1$	$\|+2\rangle + \|-2\rangle$
$\|+2\rangle + \|-1\rangle$	1/2	-	$\|+2\rangle$
$\|+1\rangle + \|0\rangle$	1/2	$\rightarrow \|+2\rangle \approx 21.7$ $\rightarrow \|-1\rangle \approx 19.2$	$\|+2\rangle$
$\|+1\rangle$	1	$\rightarrow \|+2\rangle \approx 22.4$ $\rightarrow \|0\rangle \approx 12.2$ $(\rightarrow \|-1\rangle \approx 4.7)$	$\|+2\rangle$
$\|+2\rangle$	2	-	$\|+2\rangle$

for details see: H. Schmaljohann et al., Phys. Rev. Lett. 92, 040402 (2004).

Magnetic Ground States

- **F=2**

our calculations: (quadr.Zeeman:)