Collision dynamics of ^{87}Rb spin-2 Bose-Einstein condensates

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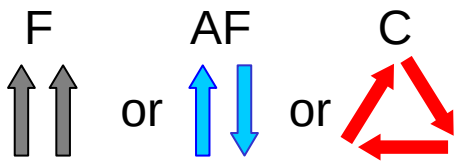
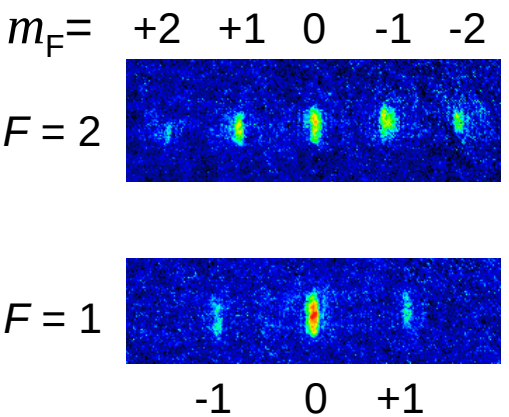
Outline

1. Spin-2 Bose-Einstein condensate (BEC)
   - Motivation: Properties of spin-2 BEC
2. Magnetic phase of spin-2 spinor BEC
   - Spin-population measurement
   - Inelastic collisions of spin-2 BEC
   - Future plan
3. Binary BECs in mixed hyperfine states
   - Two-component BECs in clock states
   -
4. Summary





1. Spin-2 Bose-Einstein condensate

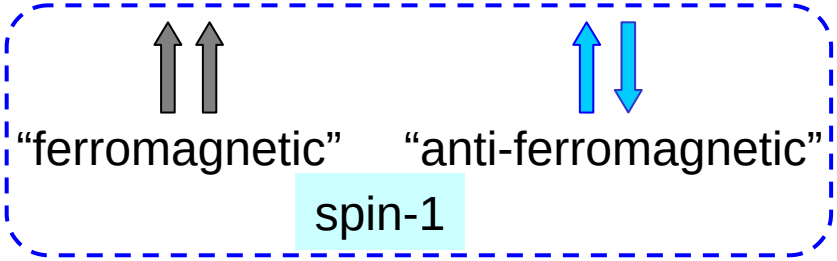
Motivation

Spin-2 Bose-Einstein condensate (BEC)

⇨ Novel physics in quantum fluids with spin degree of freedom

- Magnetic phases:

New quantum phase!



Ueda & Koashi, *PRA* **65**, 063602 (2002)

Saito & Ueda, *PRA* **72**, 053628 (2005)

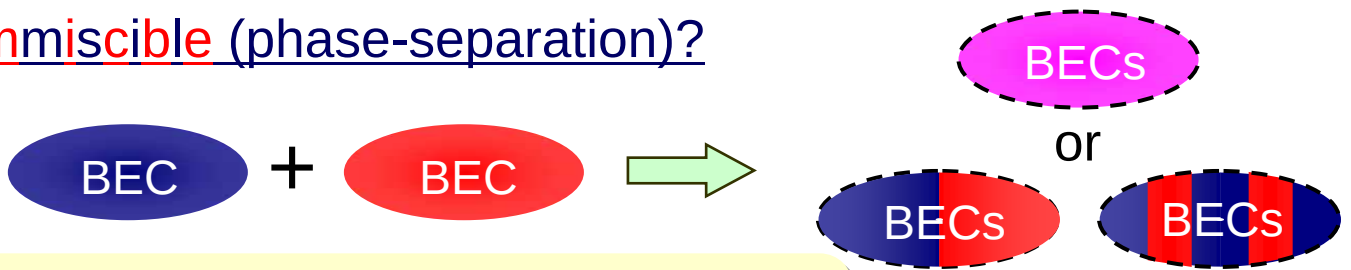
- Superfluidity:
  - Quantum vortex: multiply charged

$$n = 2 \times |m_F| = 4$$

n : vorticity,
m_F : magnetic sublevel

  - Multi-component BEC:

miscible or immiscible (phase-separation)?



Mixed hyperfine states

interplay between different magnetic phases

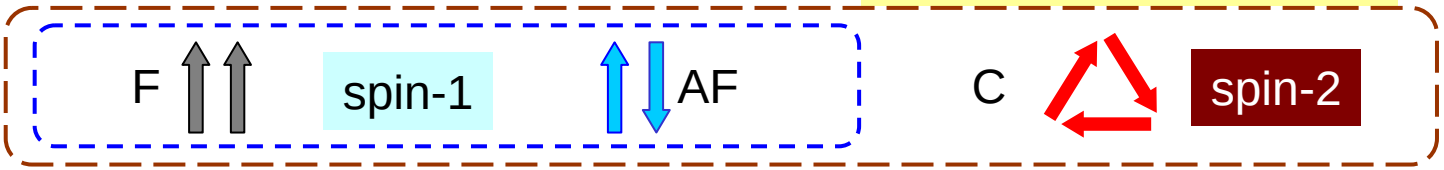
Motivation

Spin-2 Bose-Einstein condensate (BEC)

⇨ Novel physics in quantum fluids with spin degree of freedom

- Magnetic phases:

New quantum phase!



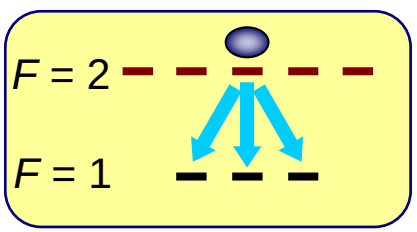
Ueda & Koashi, *PRA* **65**, 063602 (2002)

Saito & Ueda, *PRA* **72**, 053628 (2005)

- Superfluidity:
  - Quantum vortex: multiply charged
  - Multi-component BEC:
    miscible or immiscible?

Difficulty in spin-2 BEC

- Unstable BEC for spin-2 systems



trap loss!

Inelastic collisions

Ground state of BEC atoms

^{7}Li, ^{23}Na, ^{39}K, ^{87}Rb : $F = 1$ ← upper hyperfine levels for $F = 2$

^{85}Rb: $F = 2$, ^{133}Cs: $F = 3$ ← negative scattering length

^{1}H: $F = 0$, ^{4}He*, ^{174}Yb: $J = 0$, ^{53}Cr: $J = 3$

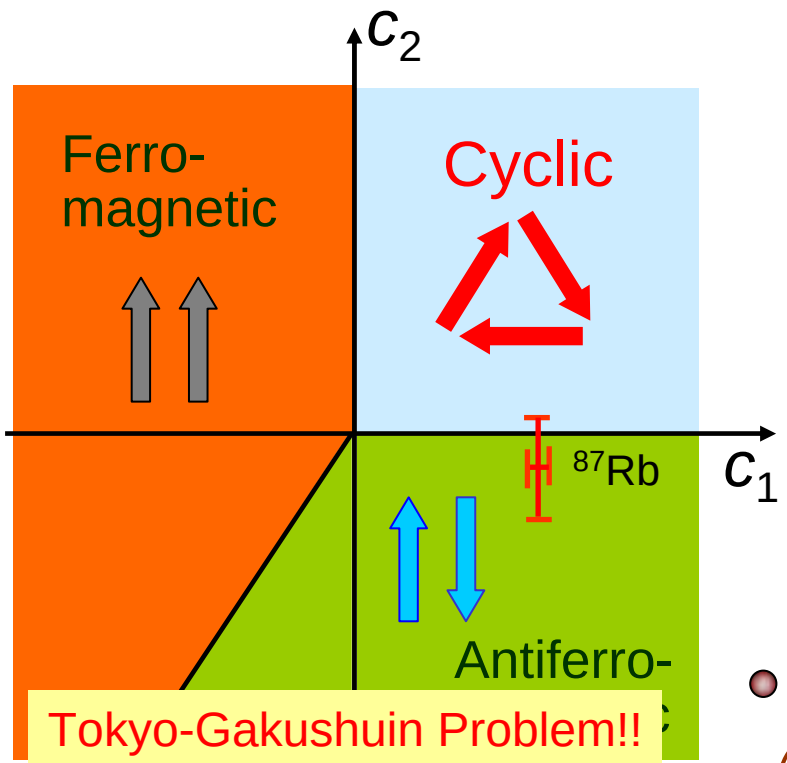
2. Magnetic phases of spin-2 spinor BEC

2-1. Spin-population measurement

Magnetic phases in spin-2 system

Phase diagram in spin-2 system

Ueda & Koashi, PRA **65**, 063602 (2002)
Saito & Ueda, PRA **72**, 053628 (2005)



Measured coefficients of spin-dependent interaction

$$c_1/\left(4\pi\hbar^2/m\right) \qquad \left(+0.99\pm0.06\right)a_B$$

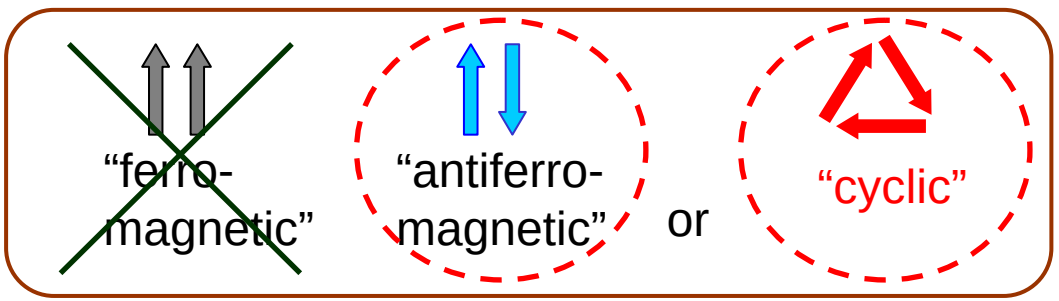
$$c_2/\left(4\pi\hbar^2/m\right) \qquad \left(-0.53\pm0.58\right)a_B$$

Widera *et al.*, *New Journal of Physics* **8**, 152 (2006)

$$c_1 = \frac{4\pi\hbar^2}{m}\frac{a_4 - a_2}{7}$$

$$c_1 = \frac{4\pi\hbar^2}{m}\frac{7a_0 - 10a_2 + 3a_4}{7}$$

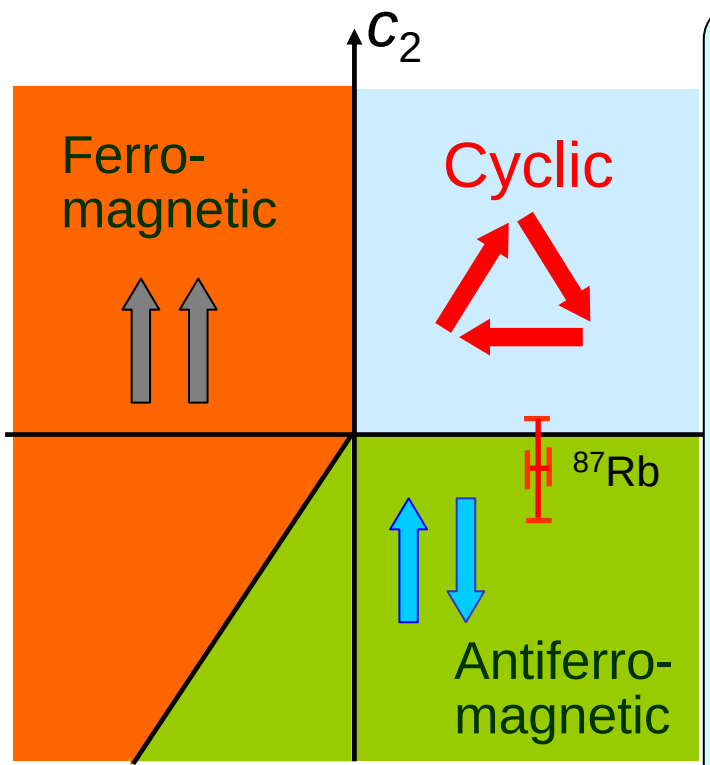
- Magnetic phases of ^{87}Rb $F = 2$:



cf. ^{87}Rb $F = 1$ "ferro-magnetic"

Magnetic phases in ^{87}Rb $F = 2$ BEC

Determination of magnetic phase using spin-population measurement



$$c_1 = \frac{4\pi\hbar^2}{m}\frac{a_4 - a_2}{7}$$

$$c_1 = \frac{4\pi\hbar^2}{m}\frac{7a_0 - 10a_2 + 3a_4}{7}$$

magnetic field strength < 100mG

initial configuration
m_F = -2 & +2

50∼300 ms evolution

m_F = **-2** & **+2**

m_F = **-2** & **0** & **+2**

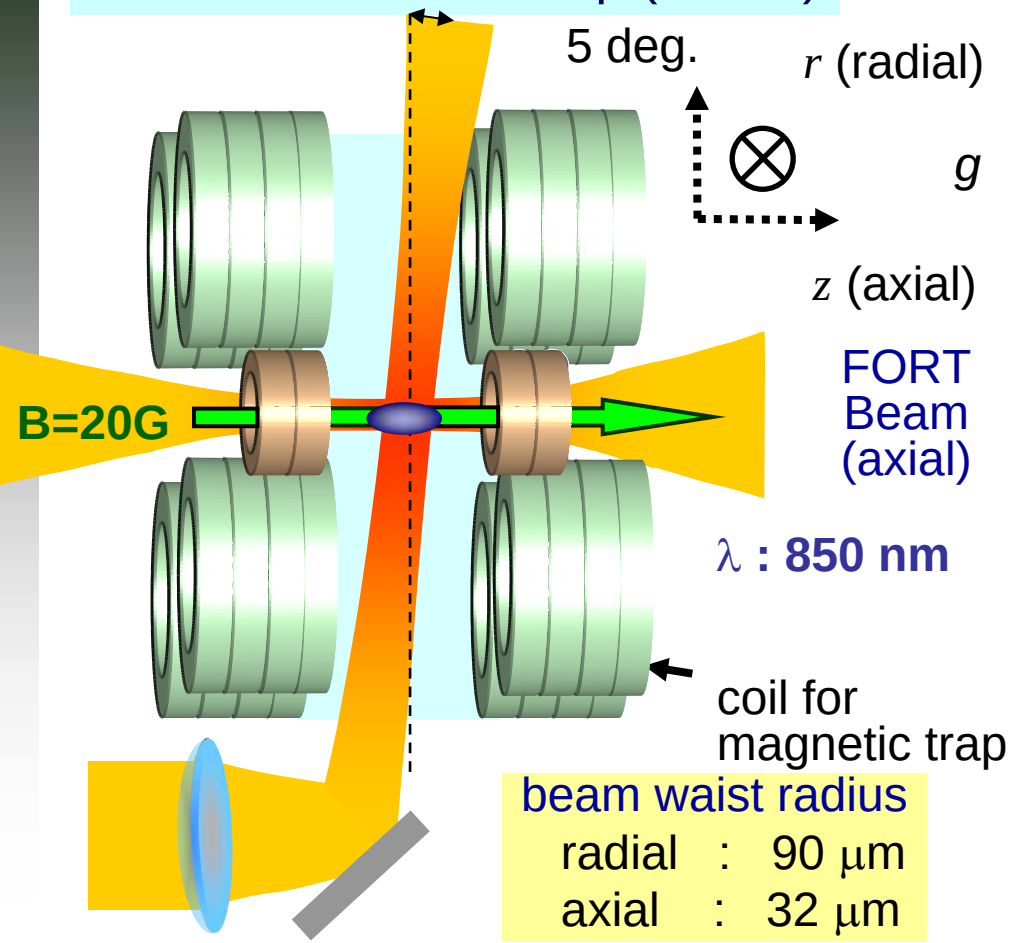
"anti-ferromagnetic"

"cyclic"

Hiroki Saito & Masahito Ueda
PRA **72**, 053628 (2005)

Optical trap (Far-Off Resonant Trap)

Far-Off Resonant Trap (FORT)



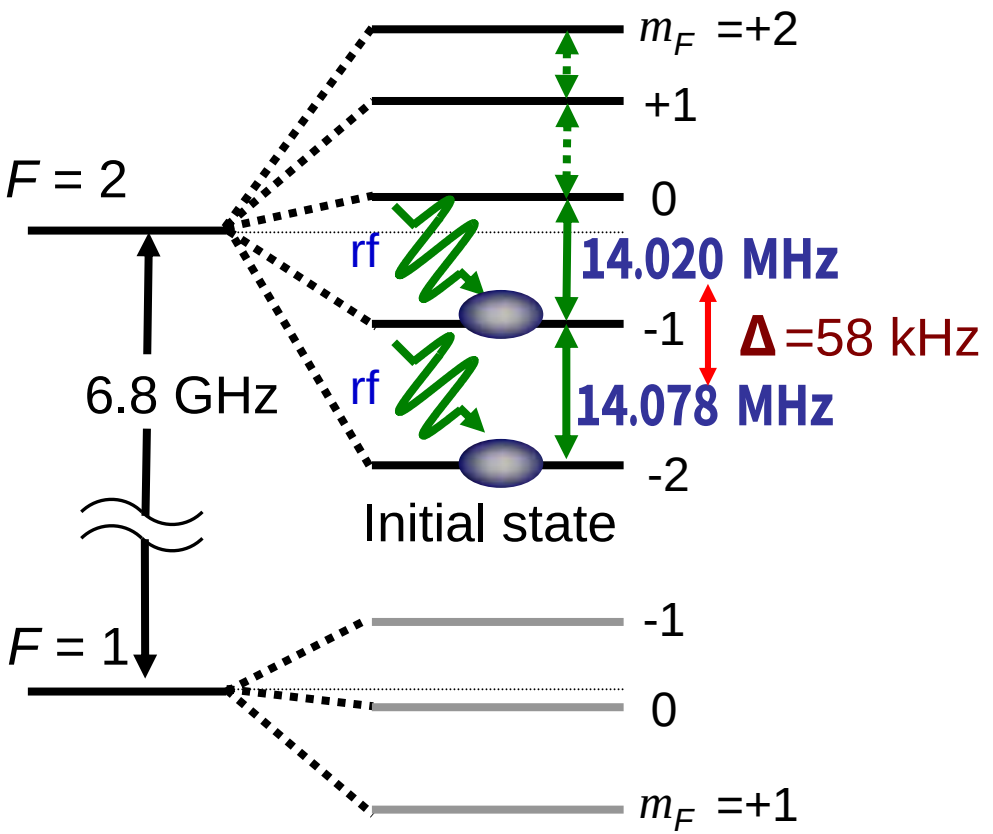
beam waist radius
radial : 90 μm
axial : 32 μm

Trap depth: ~ 1.0 μK

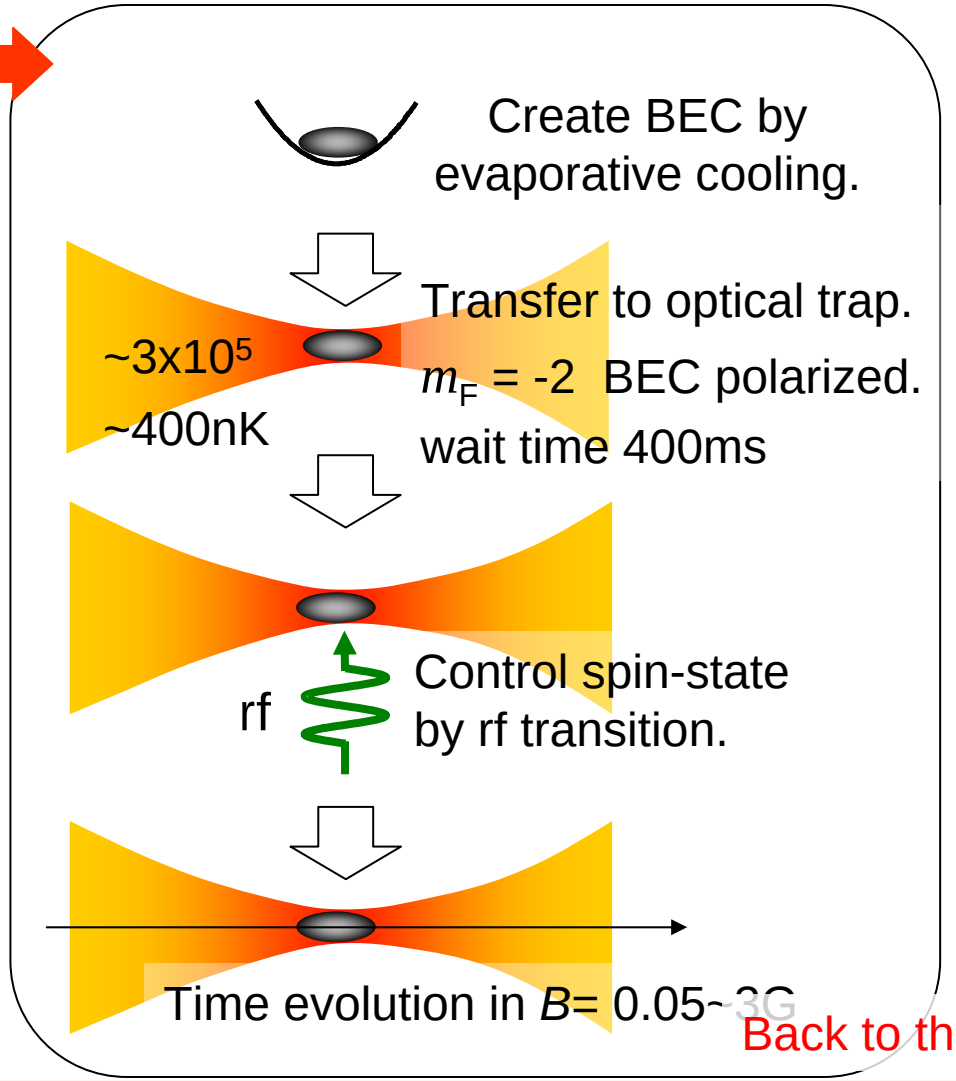
Energy level diagram of ^{87}Rb (ground hyperfine states)

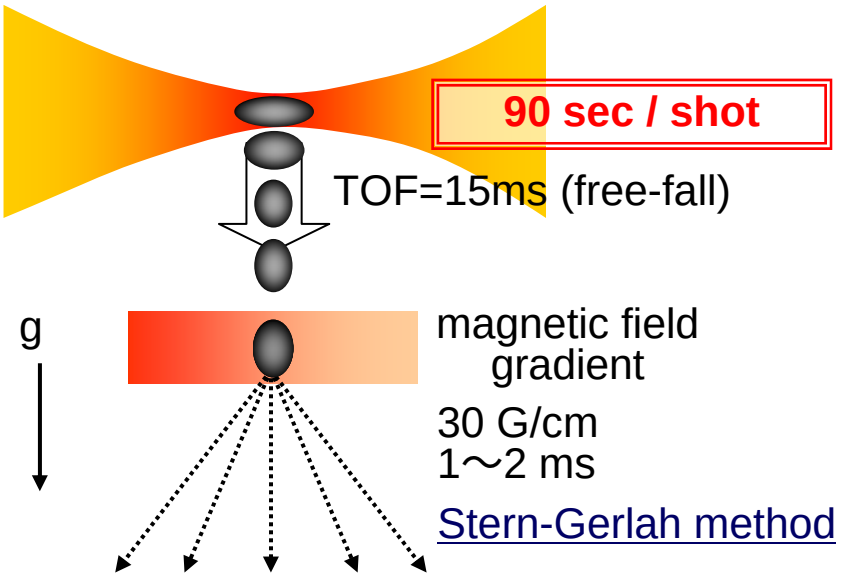
Zeeman splitting at B = 20 G

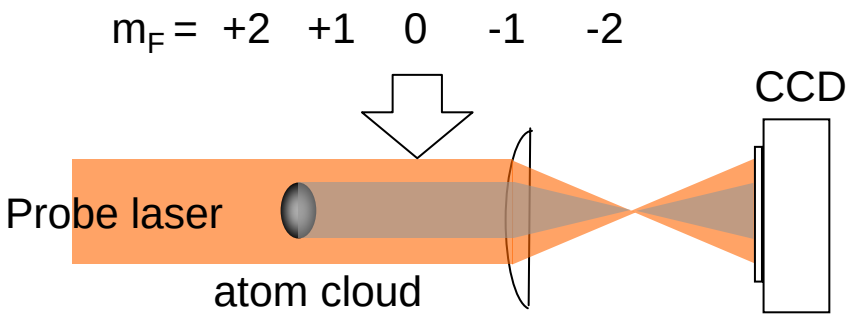
It is possible to selectively prepare any spin-states.



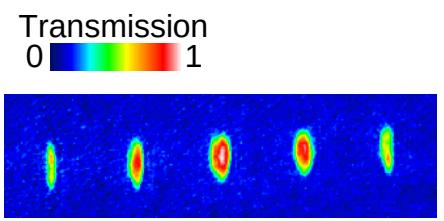
Experimental procedure







absorption imaging"

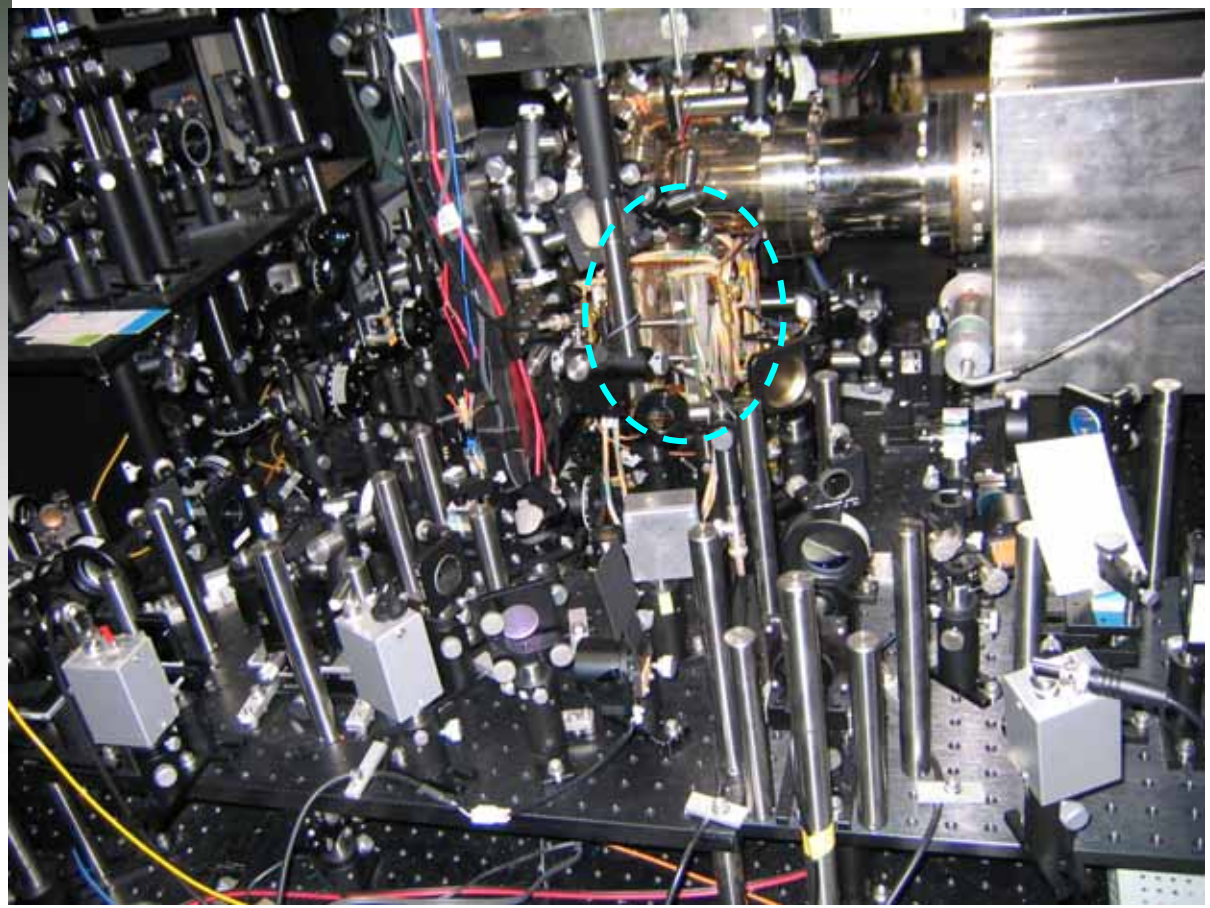


measurement of
"number of atoms"

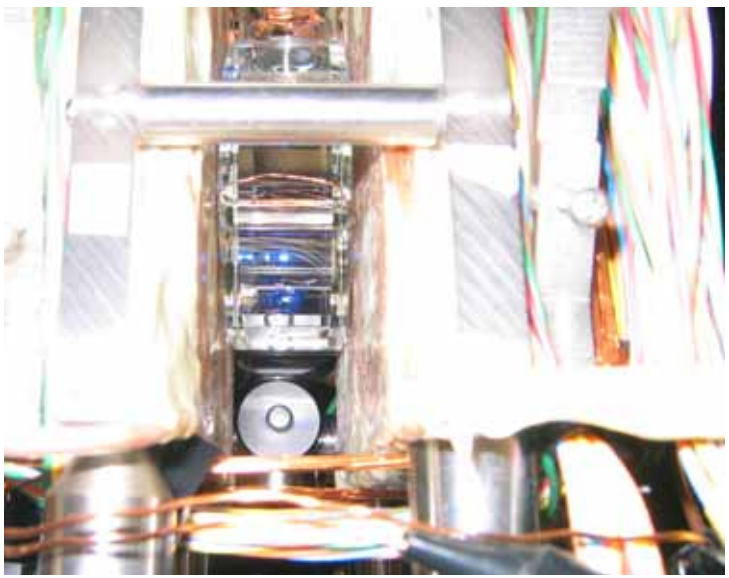
Back to the first step!

Experimental setup

BEC setup



Main chamber

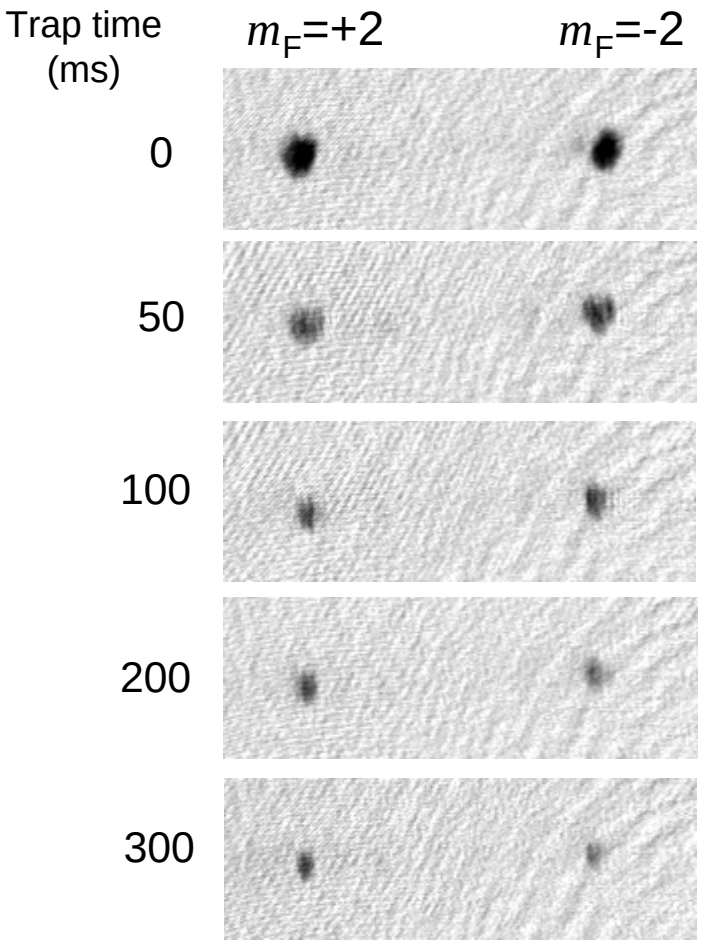


Evolution of m_F = -2 & m_F = +2 BEC mixture

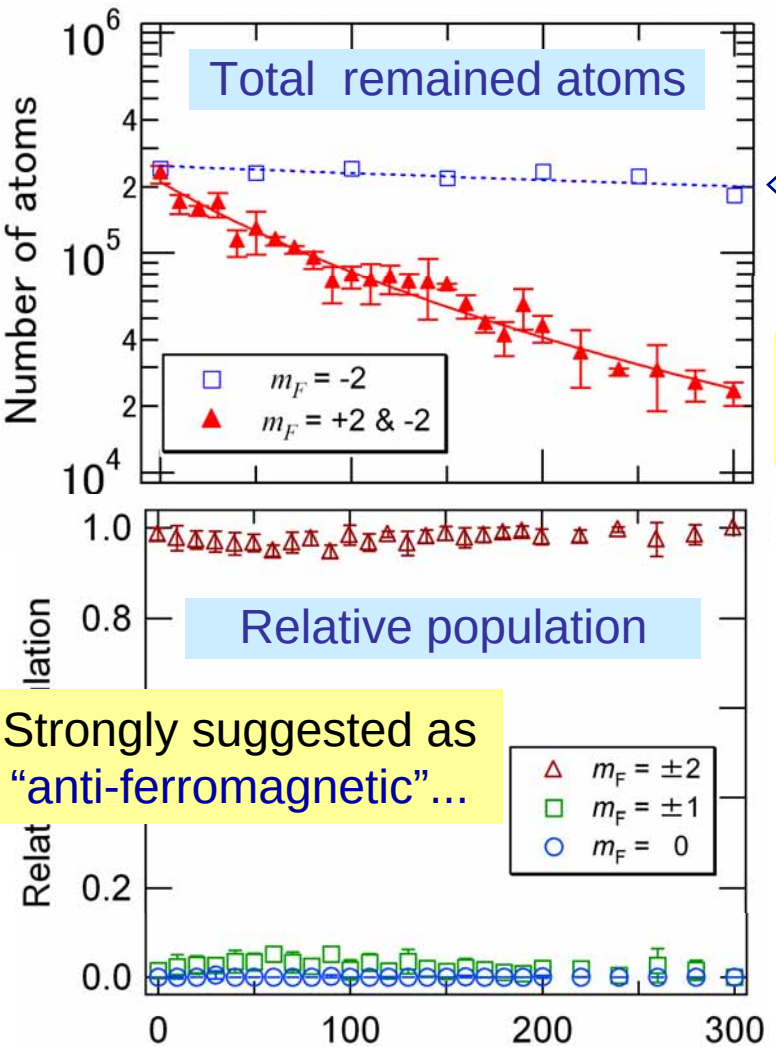
magnetic field : 45mG

initial spin-state:

$$|F=2, m_F=+2\rangle + |F=2, m_F=-2\rangle$$



No other components grew ...



⇦ Stretched state

Two-body inelastic loss rate 8.5×10^{-14} cm^{-3}/s

Strongly suggested as "anti-ferromagnetic"...

Tojo *et al.*, *Appl. Phys. B* **93**, 403 (2008)

Inelastic collision rates should be considered!!

e.g. if rate of $|2,0\rangle + |2,-2\rangle >> |2,+2\rangle + |2,-2\rangle$, $|2,0\rangle$ state cannot be observed.

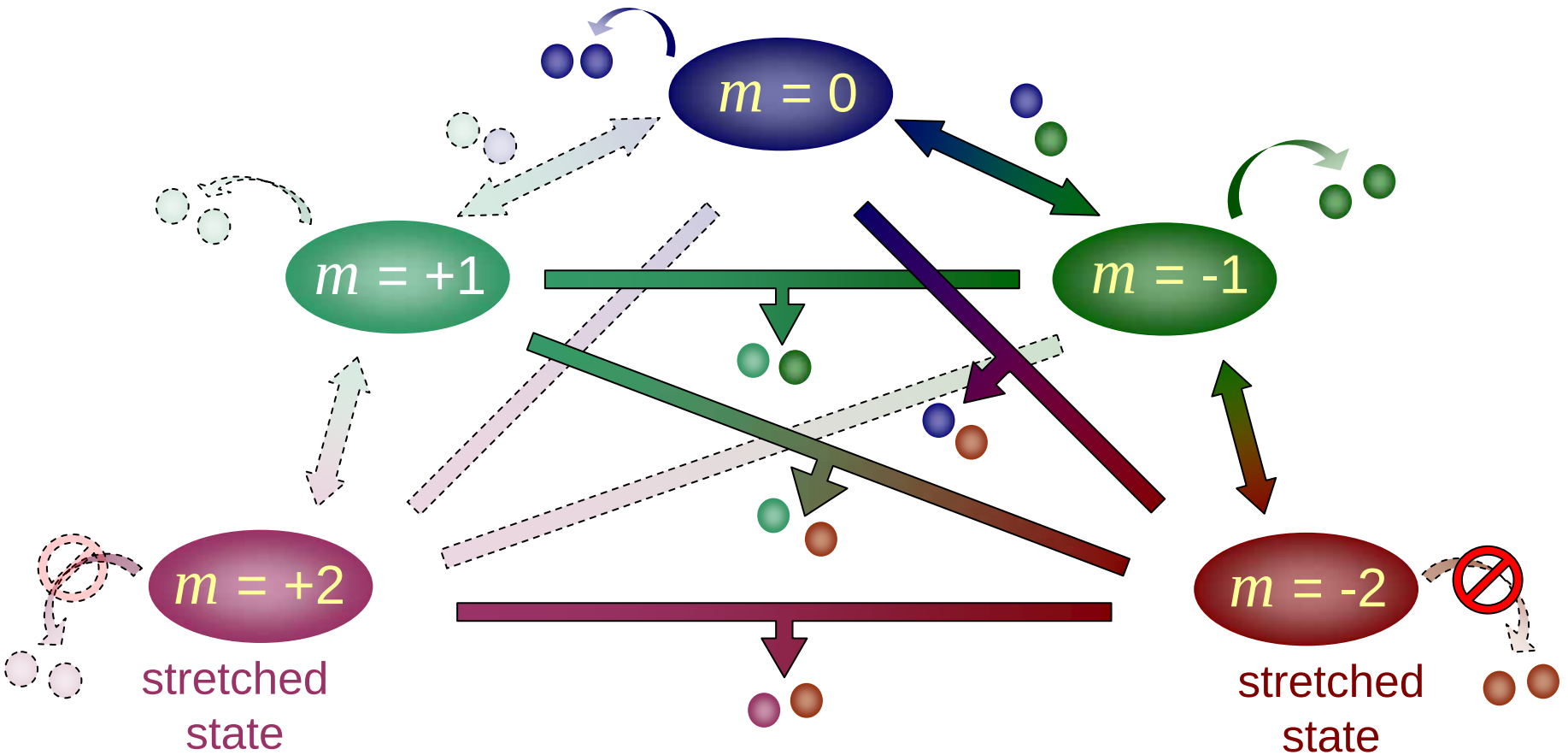
2. Magnetic phases of spin-2 spinor BEC

2-2. Inelastic collisions in spin-2 BEC

Inelastic collision of spin-2 system

- Inelastic collision of spin-2 atoms

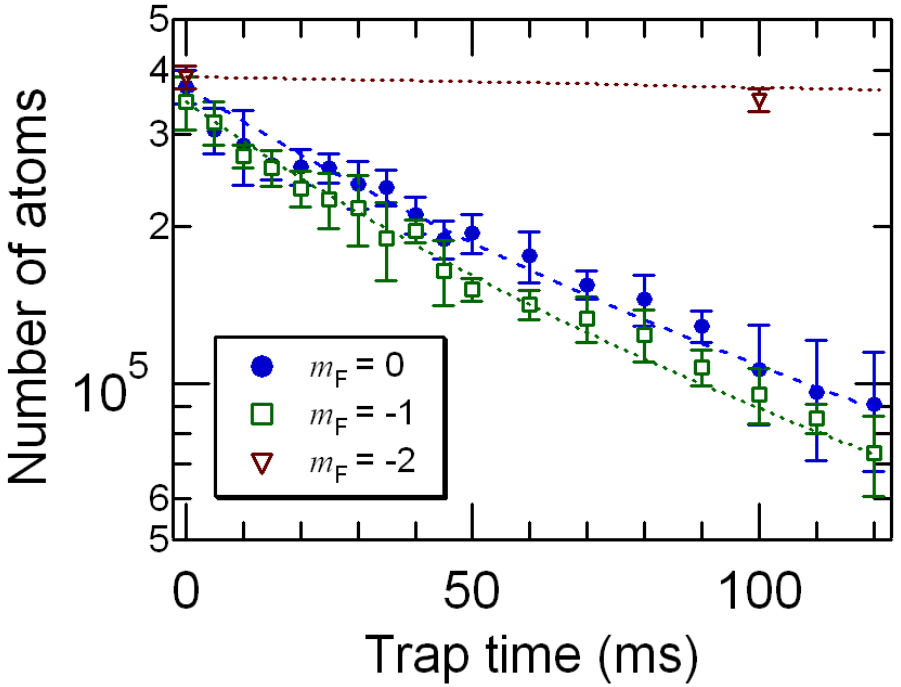
  Total spin of collision channel; $\mathcal{F}$ = 0, 2, 4

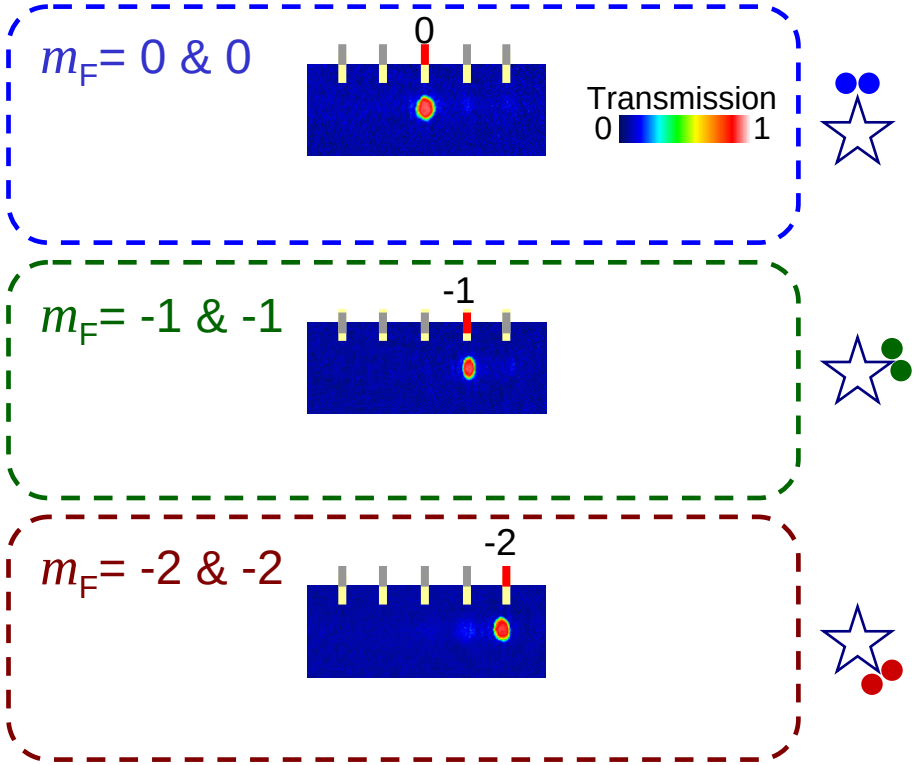


Time-evolution of identical spin state (m_F = 0, m_F= -1)

Single component BEC

magnetic field : 3.0 G





- $K_{2(-2,-2)}$ is very small!!

  ⇨ Negligible inelastic collision for $|2,-2\rangle + |2,-2\rangle$ (stretched state).

- Difference between $K_{2(0,0)}$ and $K_{2(-1,-1)}$.

Inelastic collision parameters: b_4, b_2, b_0

b_0 = ×10^{-14} cm^{-3}/s

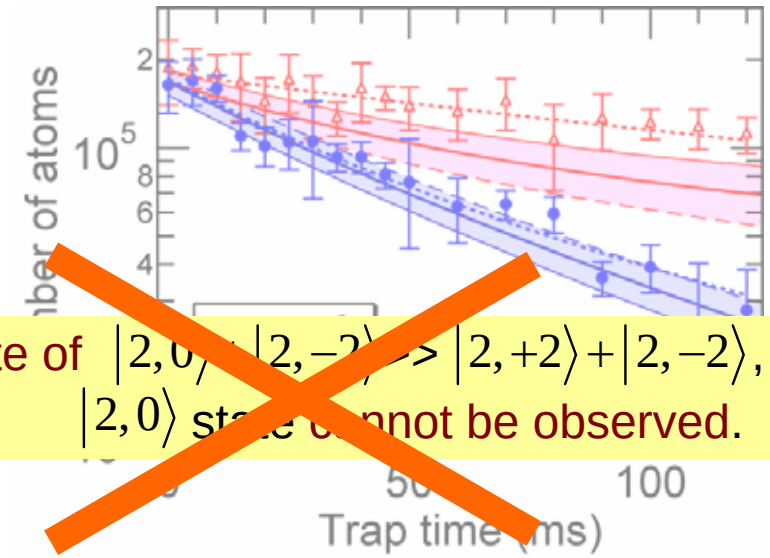
b_2 = ×10^{-14} cm^{-3}/s

b_4 = ×10^{-14} cm^{-3}/s

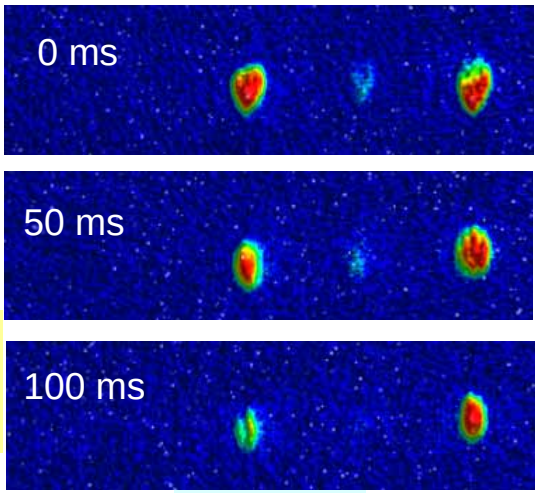
Kawaguchi, Saito, and Ueda (private communication)

Atom number evolution in $|2,0\rangle+|2,-2\rangle$ and $|2,0\rangle+|2,-1\rangle$

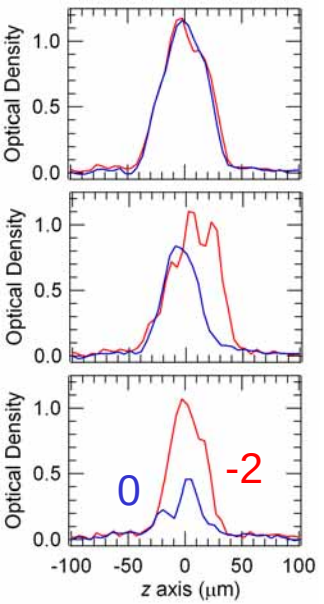
m_F= 0 and -2 magnetic field : 3.0 G



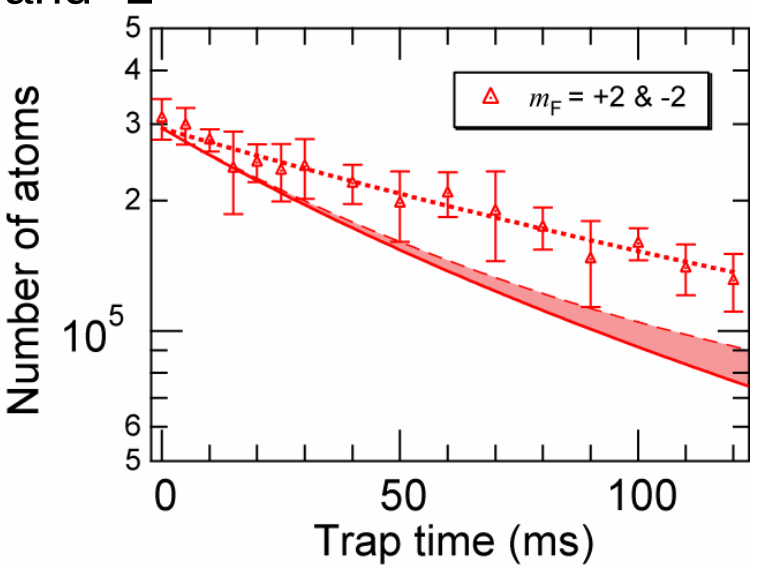
e.g. if rate of $|2,0\rangle+|2,-2\rangle \Rightarrow |2,+2\rangle+|2,-2\rangle$, $|2,0\rangle$ state cannot be observed.

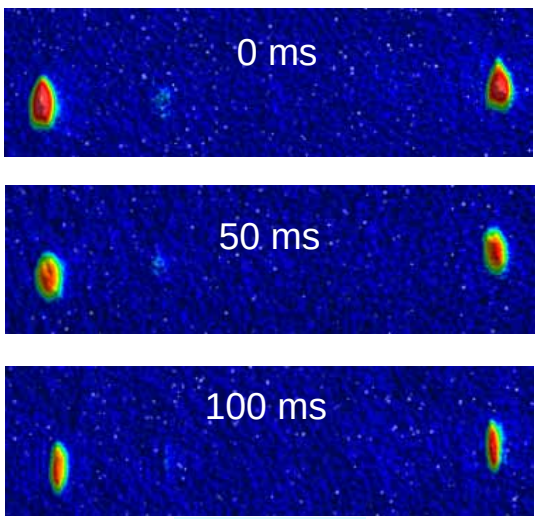


miscible

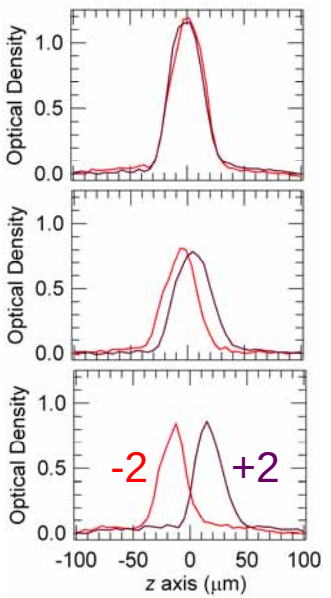


m_F= +2 and -2



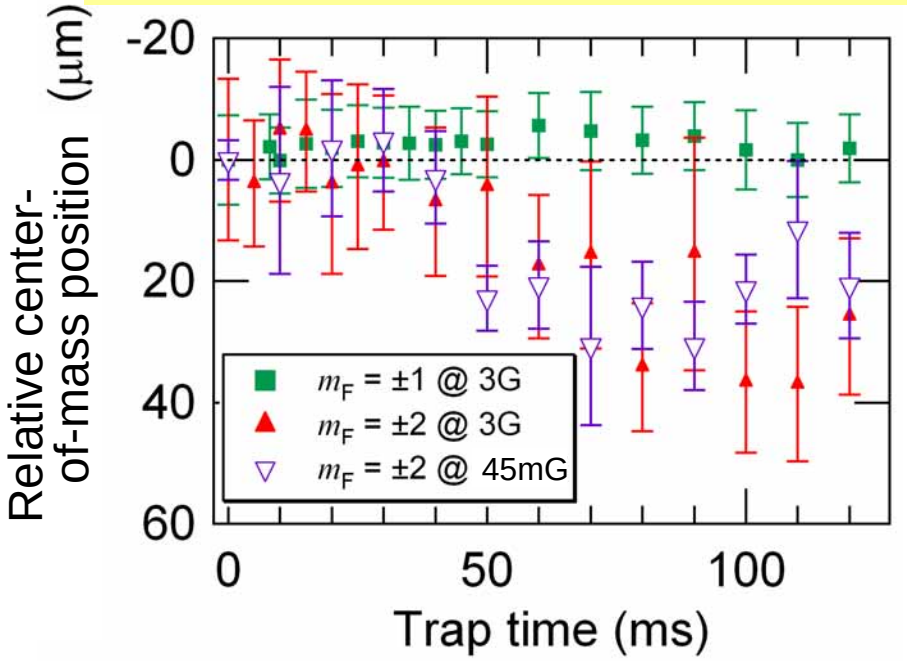


miscible

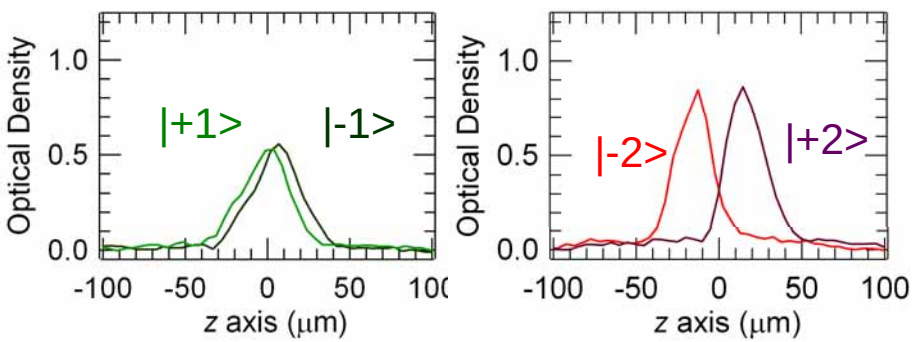


Relative displacement between different spin states

Relative center of mass position



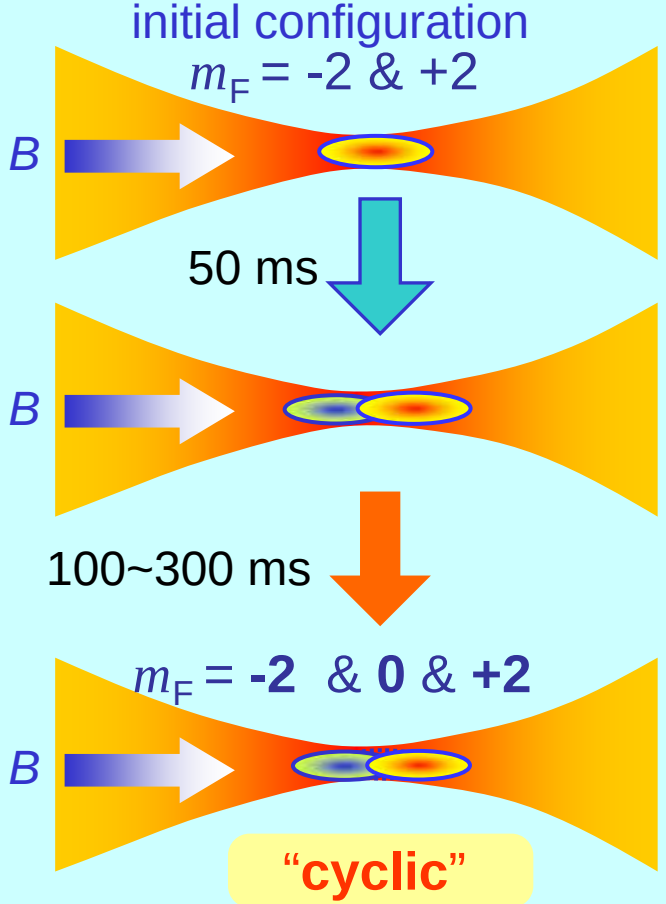
Averaged optical density in *z* axis at 100ms



overlapped

relative displacement

Spin population measurement



Relative displacement prevented production of m_F = 0 state in cyclic.

3. Binary BECs in mixed hyperfine states

3-1. Two component BECs in clock states

Binary BECs in mixed hyperfine states

^{87}Rb	m_F					
	-2	-1	0	+1	+2
F=2	-2	-1	0	+1	+2
F=1		+1	0	-1	

Phase separation of 2-component BECs

^{87}Rb |1,+1> & |2,-1>	D. S. Hall *et al*., Phys. Rev. Lett. **81**, 1539 (1998) K. M. Mertes *et al*., Phys. Rev. Lett. **99**, 190402 (2007)
^{23}Na |1,+1> & |1,0>	H.-J. Miesner *et al*., Phys. Rev. Lett. **82**, 2228 (1999) K. Kasamatsu and M. Tsubota., Phys. Rev. Lett. **93**, 100402 (2004)

|2,0> + |1,0>

???

|2,-2> & |1,-1> : oppositely sensitive to magnetic field

|2,+1> & |1,-1> : same sensitive to magnetic field

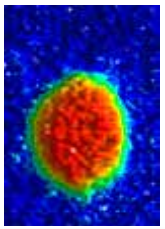
|2,0> & |1,0> : insensitive to magnetic field!!

We observed time-evolution of |1,0>+|2,0> in optical trap to prevent from effects of magnetic field.

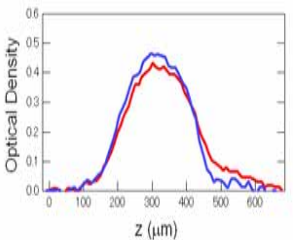
Observation of phase-separation: equal population

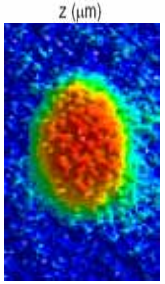
|1,0> : |2,0> ~ 0.5 : 0.5

Time evolution (ms) 0 50 100 150 200

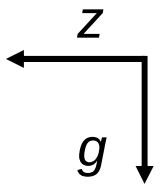


|2,0>





|1,0>



Phase-separation condition

$$\sqrt{a_{11}a_{22}} < a_{12}$$

$a_{11} = 100.86a_B$

$a_{22} = 94.57a_B$

$a_{12} = ??$

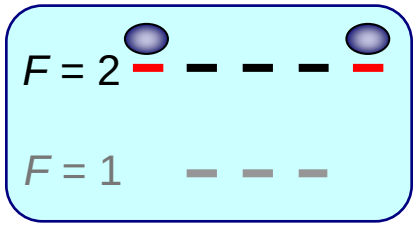
Widera *et al.*,
New J. Phys. **8**, 152 (2006)

Symmetrically separated each other

$a_{12} > 97.66a_B$?

Summary

- Magnetic phase of ^{87}Rb spin-2 BEC
  - For $m_F = \pm 2$ initial state, atoms remain in $m_F = \pm 2$
    "Anti-ferromagnetic behavior"



  - Inelastic collision rates of all possible channels are well described by two parameters: basis knowledge for future study.

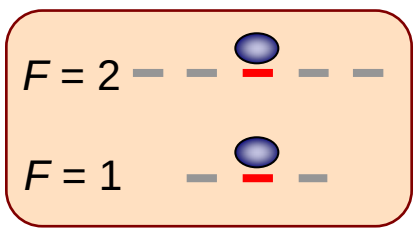
$b_0 =$, $b_2 =$, $b_4 =$

Results supported "anti-ferromagnetic" phase...
However, effects of relative displacement or phase-separation??

⇨ Future plan

- Binary BECs in mixed hyperfine states
  - Multiple domains are observed in clock states.

⇨



Thank you !!