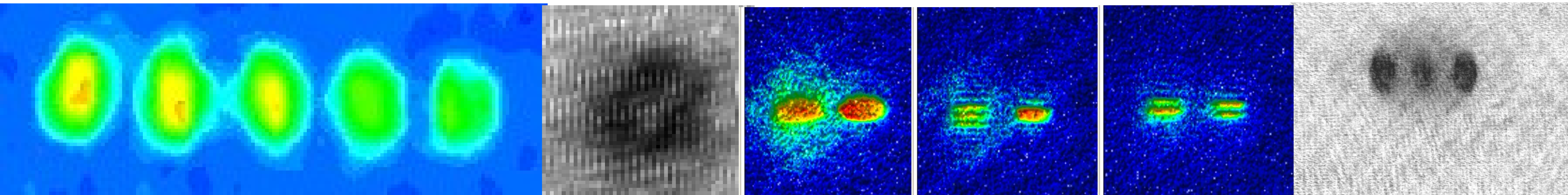
Grant-in Aid for Scientific Research on Priority Areas (Grant No. 450) from MEXT
International Symposium on Physics of New Quantum Phases in Superclean Materials
PSM 2010, Hamagin Hall “VIA MARE”, Yokohama March 11, 2010

学習院

Spin-dependent inelastic collisions in spin-2 Bose-Einstein condensates

Department of physics, Gakushuin University

Takuya Hirano



Scope of the presentation

- Poster → Aural → broaden the scope

Properties and dynamics of Bose-Einstein condensates with internal degrees of freedom

Experimental achievement in Gakushuin University

Present member: S. Tojo, T. Tanabe, Y. Taguchi, Y. Suzuki, M. Kurihara, Y. Masuyama

Spin-dependent inelastic collisions in spin-2 Bose-Einstein condensates

S. Tojo, T. Hayashi, T. Tanabe, T. Hirano,
Y. Kawaguchi, H. Saito, M. Ueda

Phys. Rev. A **80,** 042704 (2009).

maybe technical,
but fundamental knowledge
to understand spinor BEC

Experiment

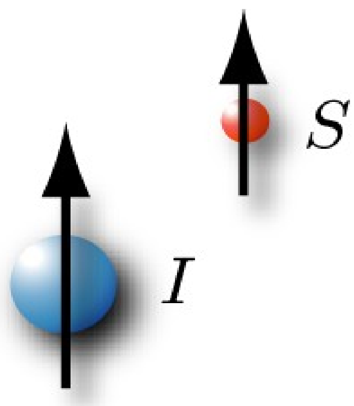
Theory

Theory

Research objectives: Why atomic BEC with internal degrees of freedom

Internal degrees of freedom

- Scalar BEC: spin state is fixed (magnetic trap)
- Spinor BEC: spin degrees of freedom are librated (optical trap)
- hyperfine spin



$$\boldsymbol{F} = \boldsymbol{S} + \boldsymbol{L} + \boldsymbol{I}$$

$\boldsymbol{S}$: electron spin

$\boldsymbol{L}$: electron orbital

$\boldsymbol{I}$: nuclear spin

^{87}Rb, ^{23}Na, ^{7}Li, ^{41}K	F =1, 2
^{85}Rb	F =2, 3
^{133}Cs	F =3, 4
^{52}Cr	F =3 (S =3, I =0)
^{4}He*, ^{40}Ca, ^{174}Yb, ^{176}Yb	F =0 (S =0, I =0)

unstable

All spin states can be trapped in an optical trap

⇩

Novel physics in qantum fluids with many internal degrees of freedom

Rb BEC with internal degrees of freedom

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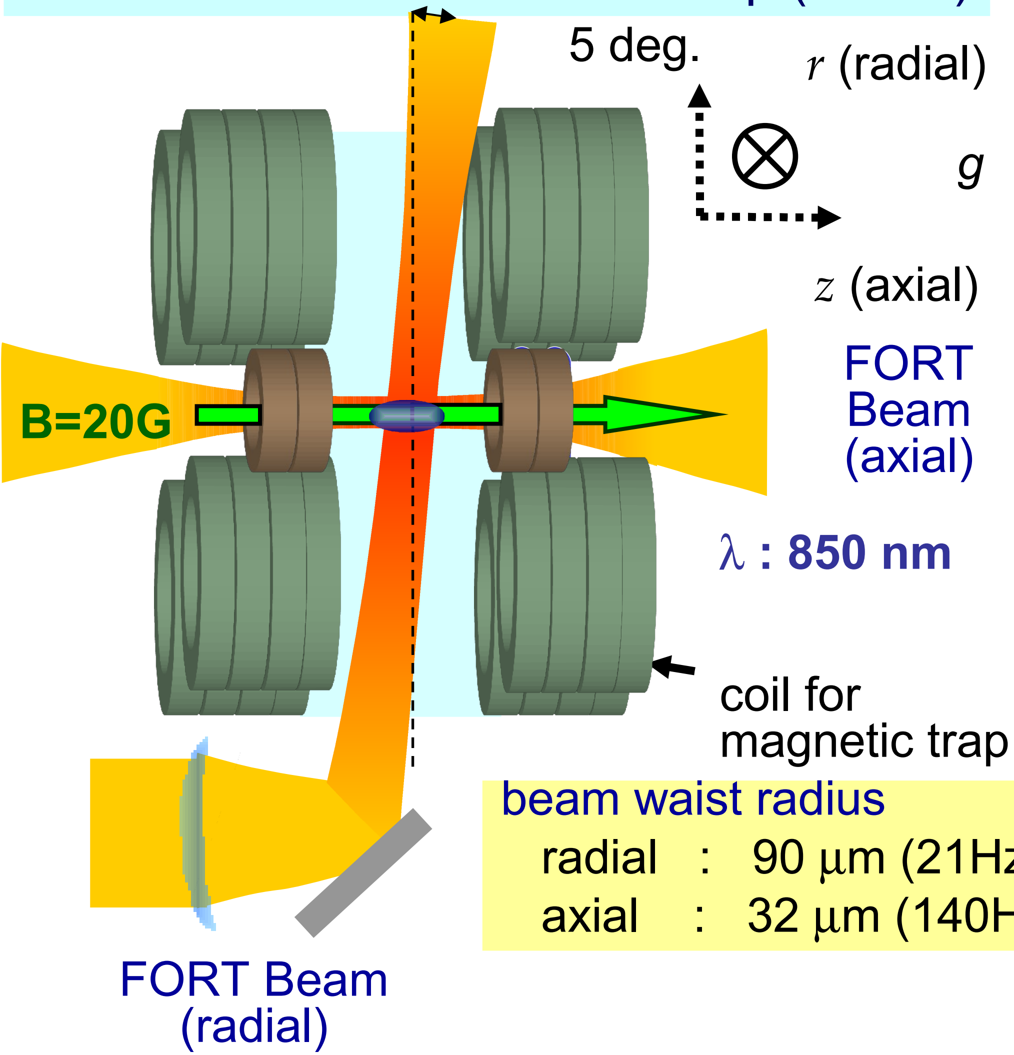
^{87}Rb	high-field seeker		m_F	low-field seeker	
F=2	-2	-1	0	+1	+2
F=1		+1	0	-1	

- Magnetic sublevels can be coherently coupled, and their populations can be controlled.
- Scattering lengths can be controlled by Feshbach Reaonance.
- Phase separation of two-component BEC

I would like to briefly report our experimental results on
"Controlling phase-separation
of binary Bose-Einstein condensates
by mixed-spin-channel Feshbach resonance"

Experimental setup and spin-state manipulation

Crossed Far-Off Resonant Trap (FORT)

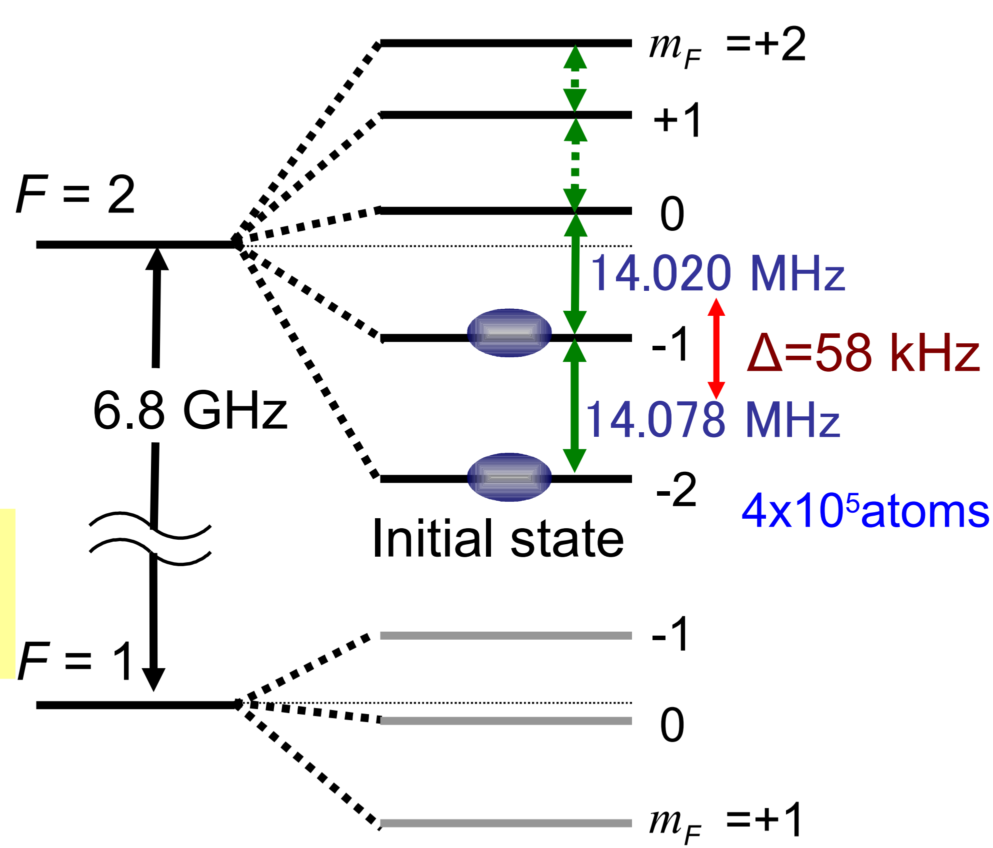


beam waist radius
radial : 90 μm (21Hz)
axial : 32 μm (140Hz)

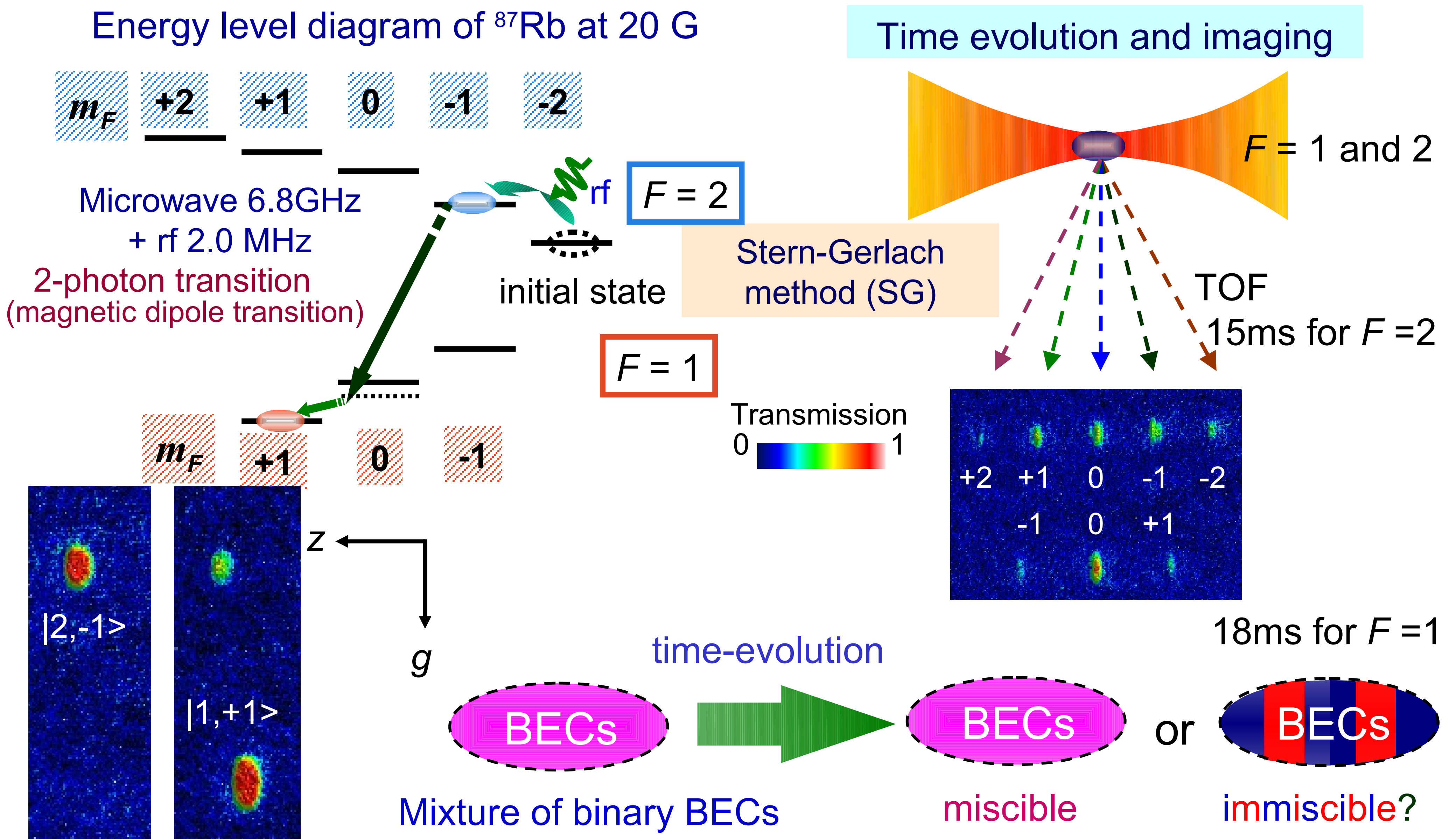
Trap depth: ~ 1.0 μK

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

Zeeman splitting at B = 20 G



Spin-state manipulation



Rb BEC with internal degrees of freedom

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^{87}Rb	high-field seeker		m_F	low-field seeker	
F=2	-2	-1	0	+1	+2
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・Magnetic sublevels can be coherently coupled, and their populations can be controlled.

・Scattering lengths can be controlled by Feshbach Reaonance.

・Phase separation of two-component BEC

・Ground-state phase of ^{87}Rb BEC

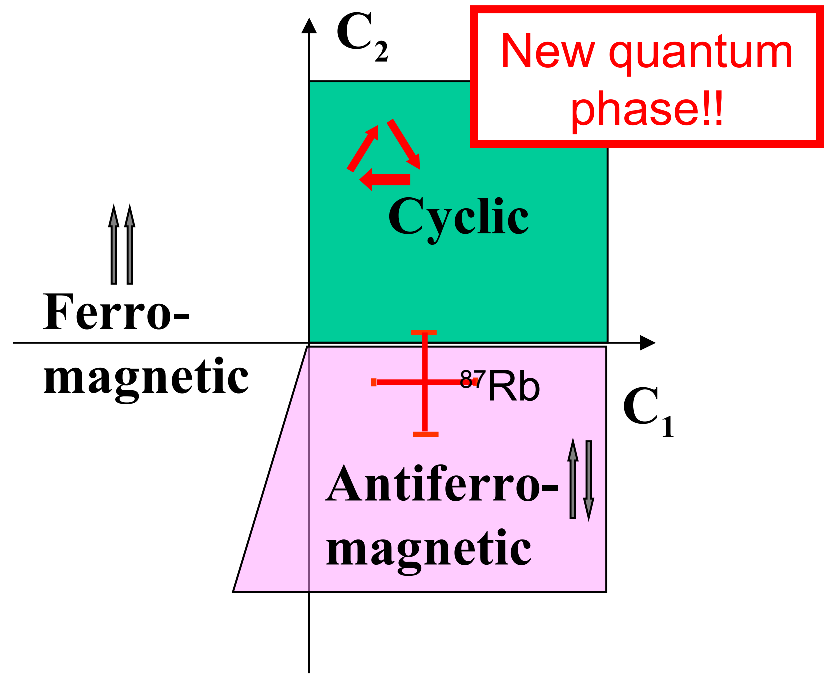
Rb BEC with internal degrees of freedom

^{87}Rb	high-field seeker		m_F	low-field seeker	
F=2	-2	-1	0	+1	+2
F=1		+1	0	-1	

- Ground-state phase of ^{87}Rb BEC

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

$$c_2 = \frac{4\pi\hbar^2}{m}\frac{7a_0 - 10a_2 + 3a_4}{7}$$



Measured coefficients

$c_1 / (4\pi\hbar^2/m)$	$(+0.99 \pm 0.06)\, a_B$
$c_2 / (4\pi\hbar^2/m)$	$(-0.53 \pm 0.58)\, a_B$

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

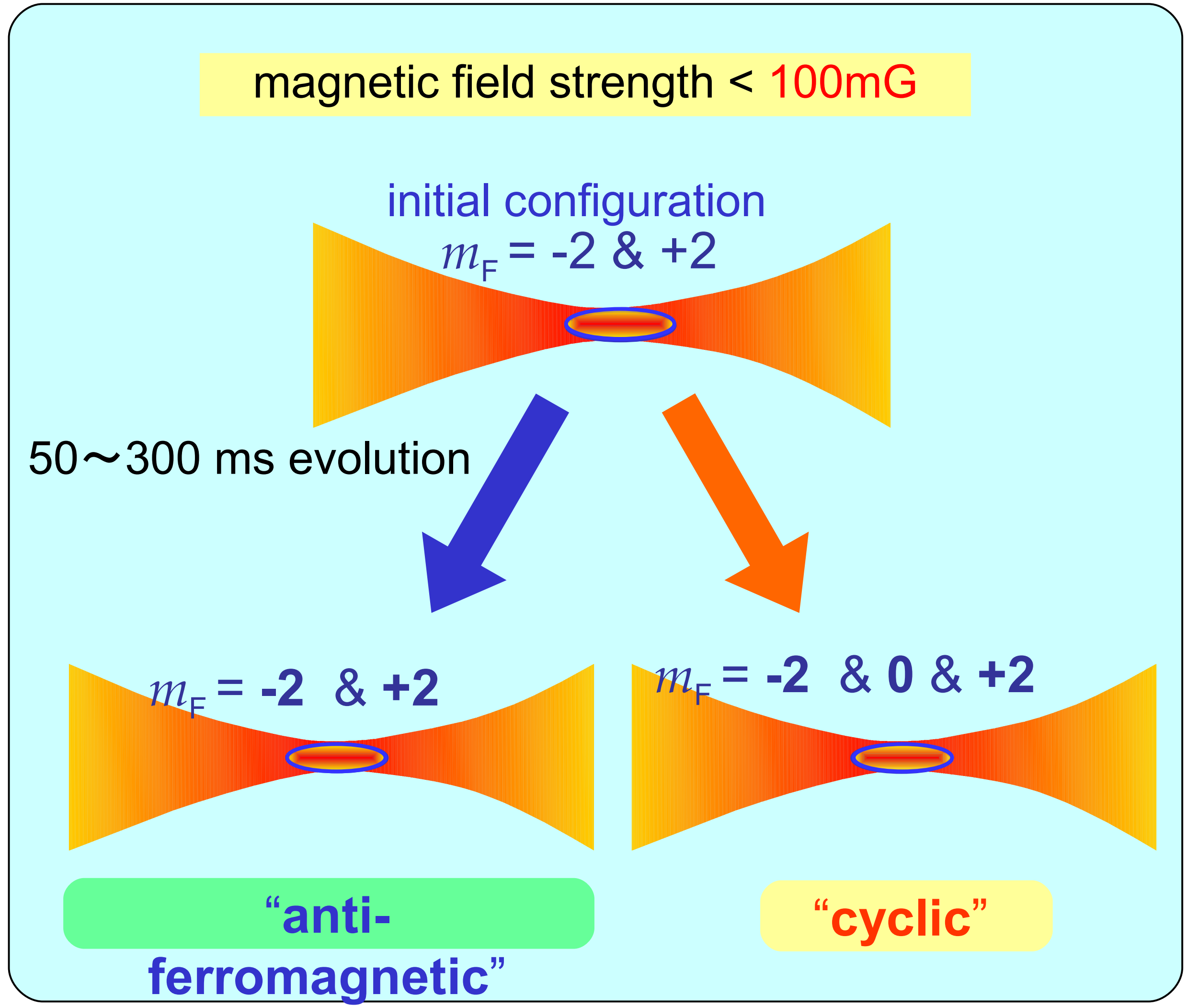
Ciobanu, Yip, & Ho, PRA 61, 033607 (2000).
Koashi & Ueda, PRL84, 1066 (2000).

Diagnostics for the ground-state phase of a spin-2 Bose-Einstein condensate

Saito and Ueda proposed a method to determine the ground-state phase of spin-2 ^{87}Rb BEC at zero magnetic field using spin exchange dynamics.

If the F = 2 ^{87}Rb BEC has anti-ferromagnetic properties, the mixture of $m_F = -2$ and $m_F = +2$ is one of the ground states at a zero magnetic field. [M.Ueda & M.Koashi, PRA, 65, 063602 (2002)]

If m_F=0 atoms appears for the initial mixture of $m_F = -2$ and $m_F = +2$, then the ground state is cyclic.

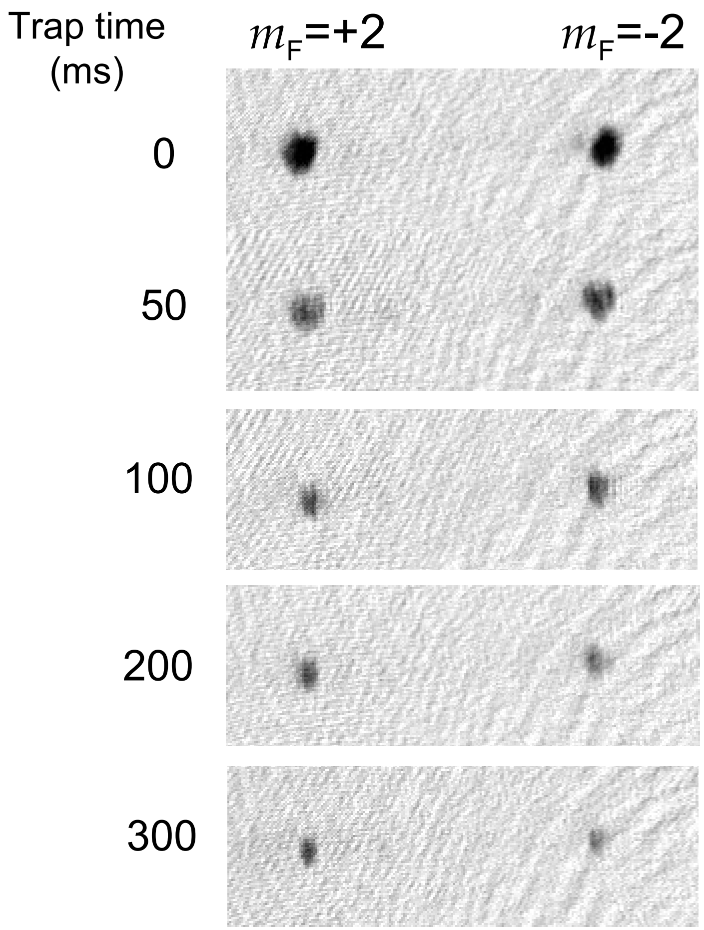


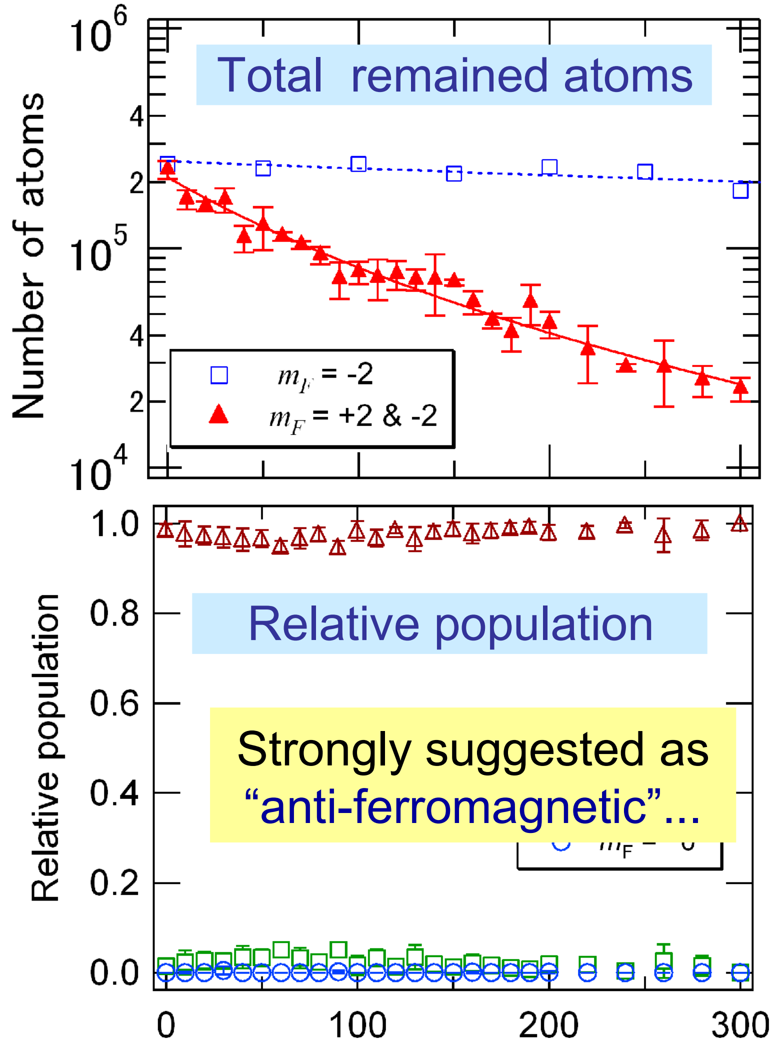
Hiroki Sato & Masahito Ueda, Phys.Rev.A 72, 053628 (2005).

Time-evolution of m_F = -2 & m_F = +2 BECs @ 45 mG

magnetic field : 45mG

initial spin-state: m_F=-2 & m_F=+2





Stretched state

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

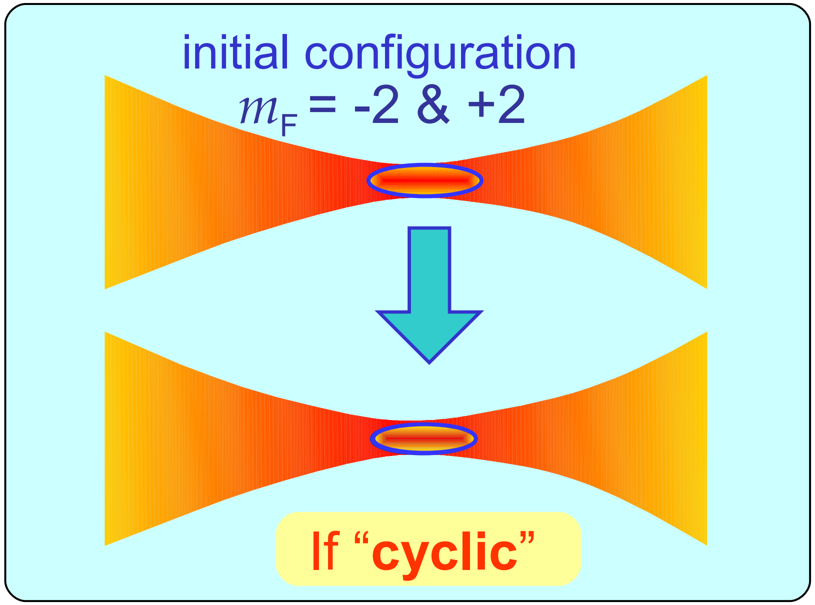
ST *et al*., Appl. Phys. B **93**, 403 (2008).

However, Trap time (ms)

No other spin states appeared

Several problems should be considered!!

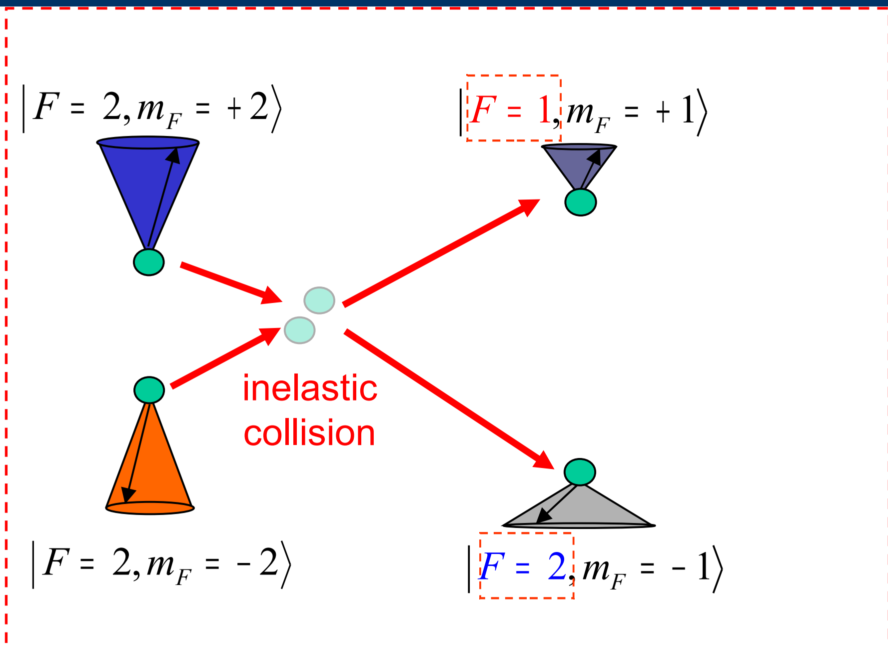
Problem-1: Inelastic collisions of F=2 states

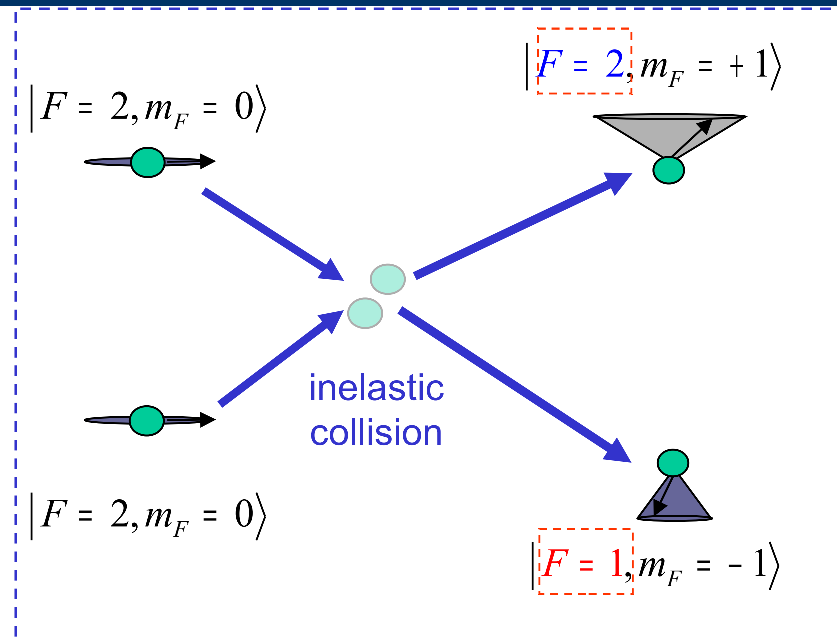


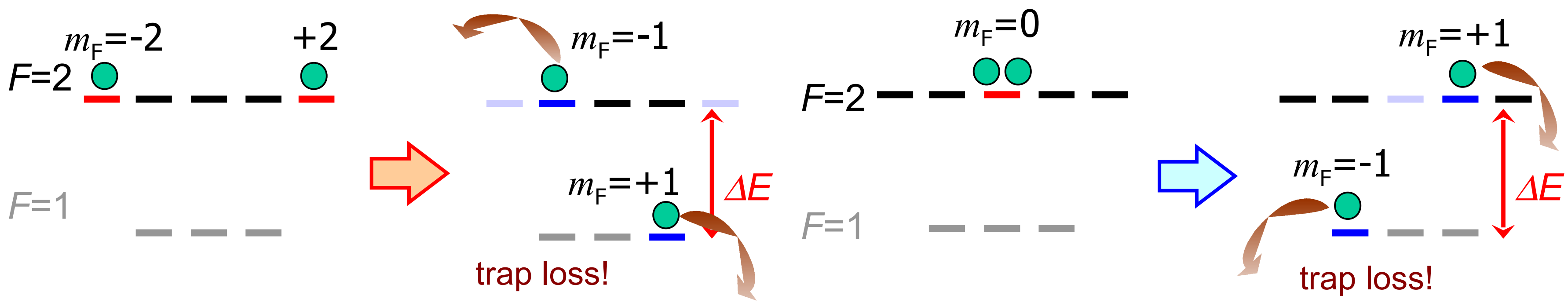
If the inelastic collision rate of m_F=0 state is much larger than that of another states, it may be difficult to observe m_F=0 state when creation rate is small.

Two-body inelastic collision

Hyperfine changing collision







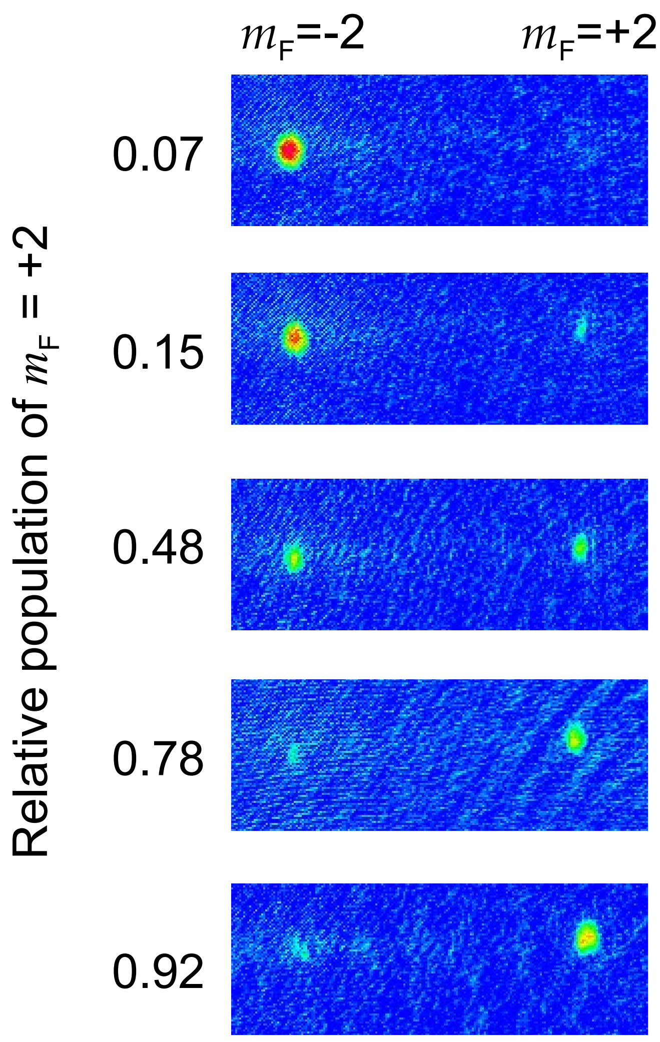
Recipient energy: <u>ΔE > 300mK</u> >> BEC: < 100 nk
Trap depth: ~ 1 μK

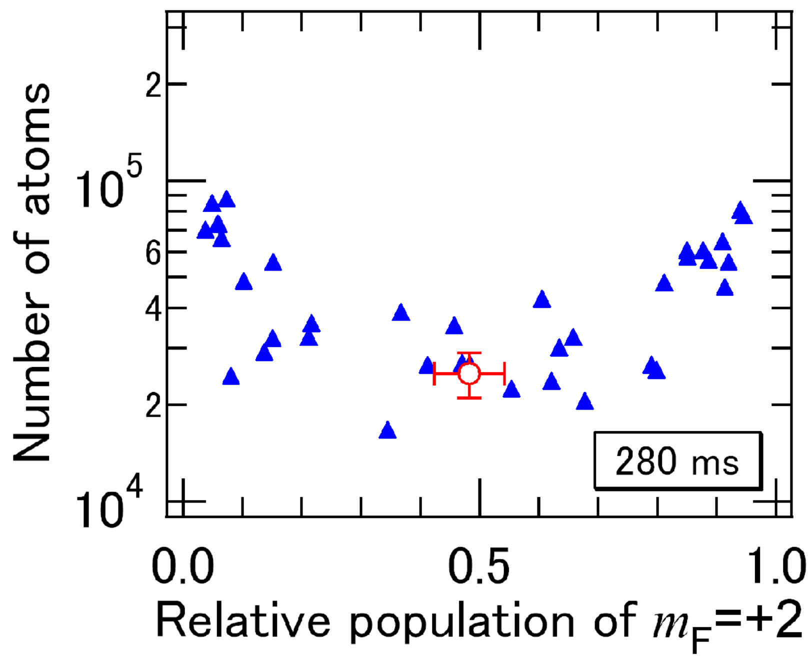
Inelastic collision between different spin-states

Dependence of remained atoms on population imbalance

S. Tojo, et *al*. APB 92, 403 (2008).

Trap time: 280 ms





; averaged data between 0.45 and 0.55

The total number of atoms at balanced population is lowest.

Two-body inelastic collision rate for spin states

2-body loss for intra-spin state (m_F=0)

$$\frac{dN}{dt} = -K_2 c_2 N^{7/5}, \qquad c_2 = \frac{15^{2/5}}{14\pi}\left(\frac{m\overline{\omega}}{\hbar\sqrt{\overline{a}}}\right)^{6/5}$$

Söding et.al., Appl. Phys. B 69,257 (1999)

$\overline{a}$: averaged scattering lentgh
$\overline{\omega}$: averaged trap frequency

2-body loss for each inter-spin states (m_F=+2&-2)

$$\frac{dN_\alpha}{dt} = \frac{dN_\beta}{dt} = -K_{2(\alpha,\beta)} \langle n_\beta \rangle N_\alpha$$

$$\langle n_\beta \rangle = [\ dv n_\alpha(\mathbf{r}) n_\beta(\mathbf{r})] / N$$

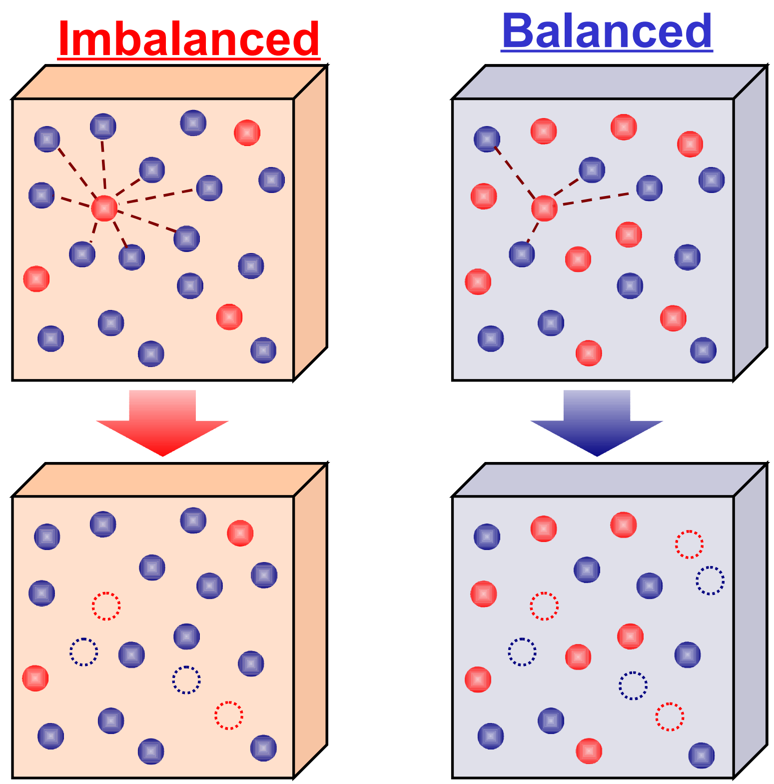
Total 2-body loss at population imbalance

$$\frac{dN}{dt} = -\rho_\alpha(t)\rho_\beta(t) K_2 c_2 N^{7/5}$$

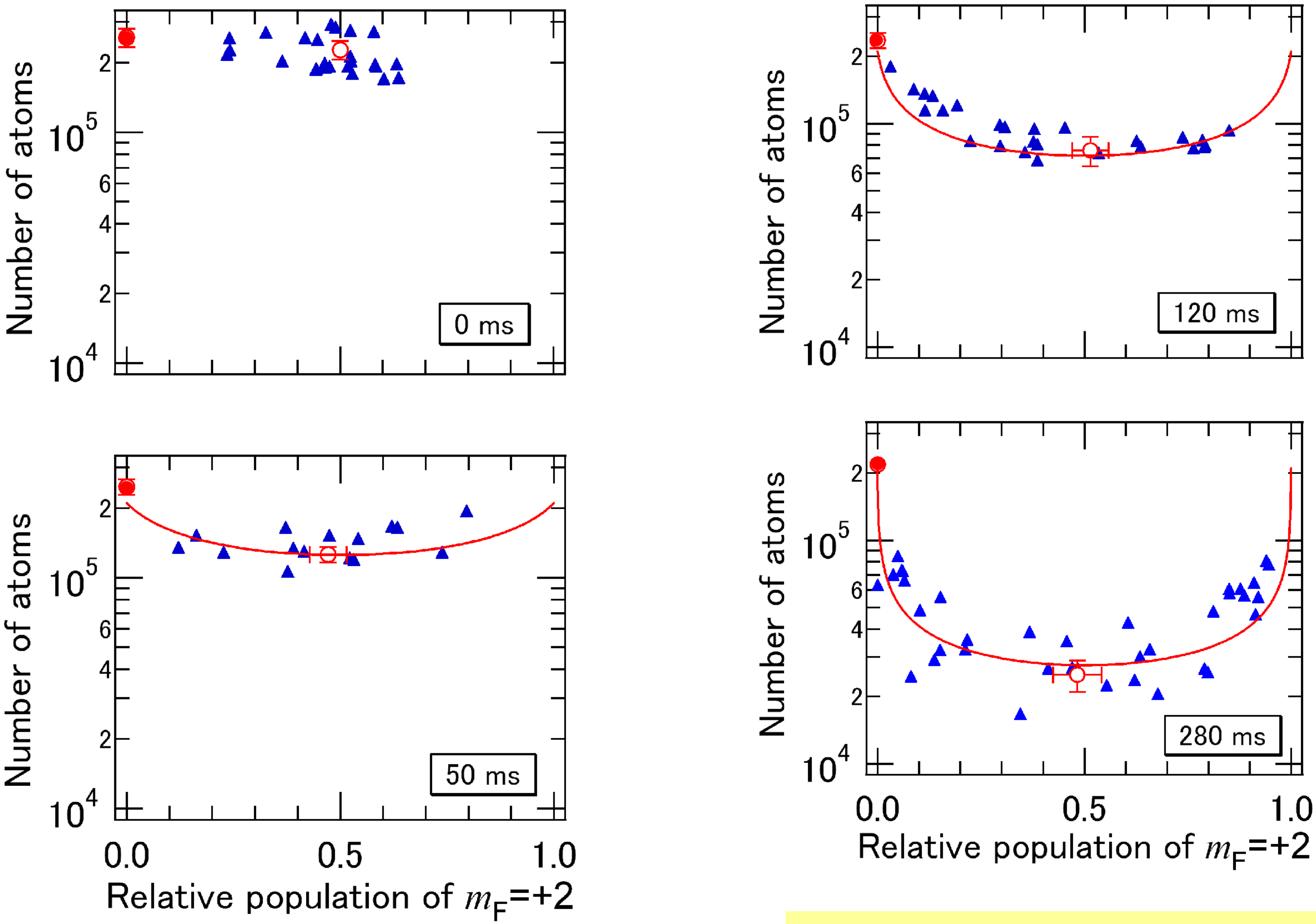
$\rho_\alpha(t)$, $\rho_\beta(t)$: relative population

$K_2 = 2K_{2(\alpha,\beta)} = 2K_{2(\beta,\alpha)}$ (normalized)

A pair with different spin states selectively decays.



Population-dependence of atom loss



● ; stretched-state initially prepared.

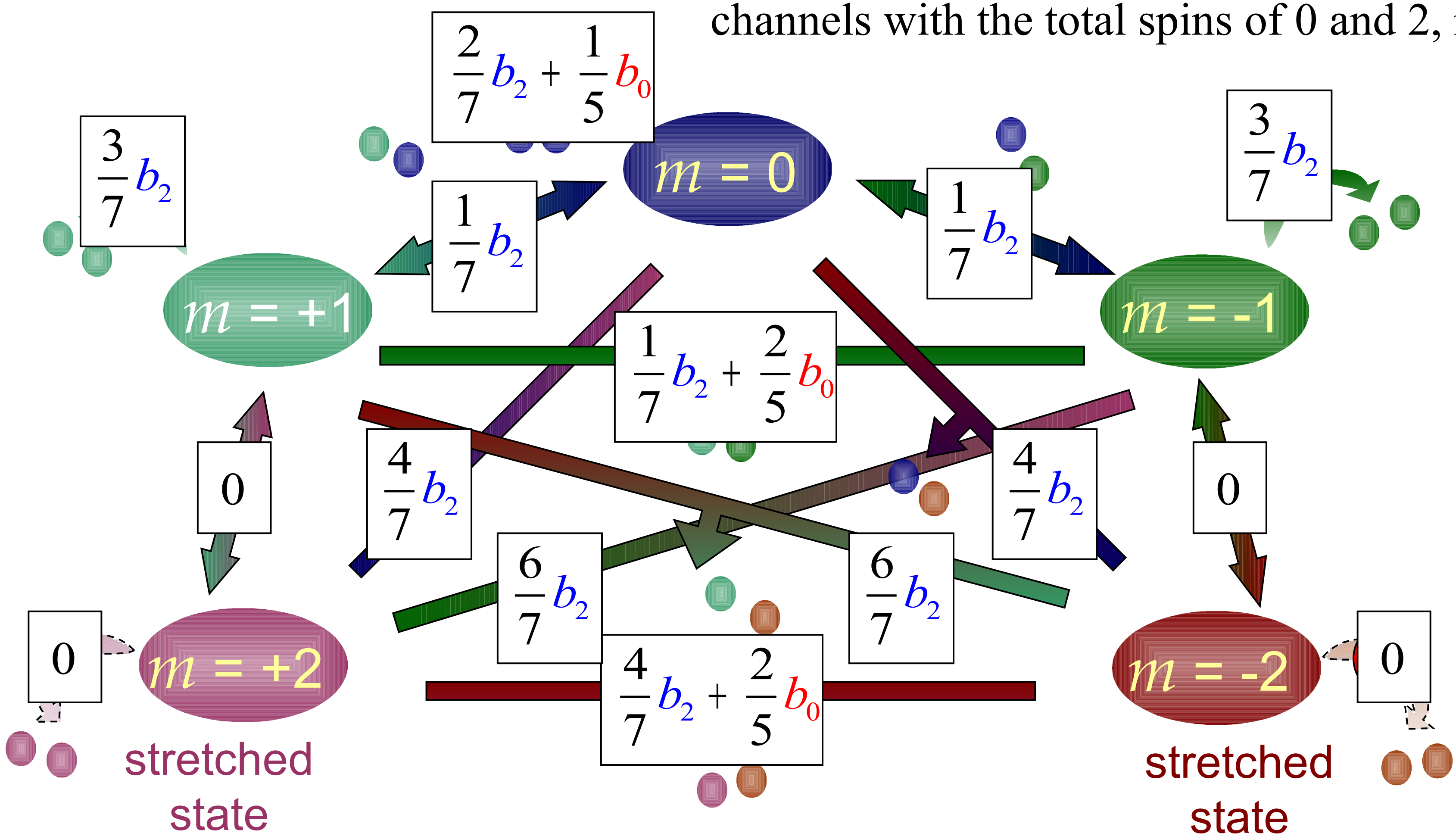
-○-; averaged data between 0.45 and 0.55

Calculations are in good agreement with experiments!!

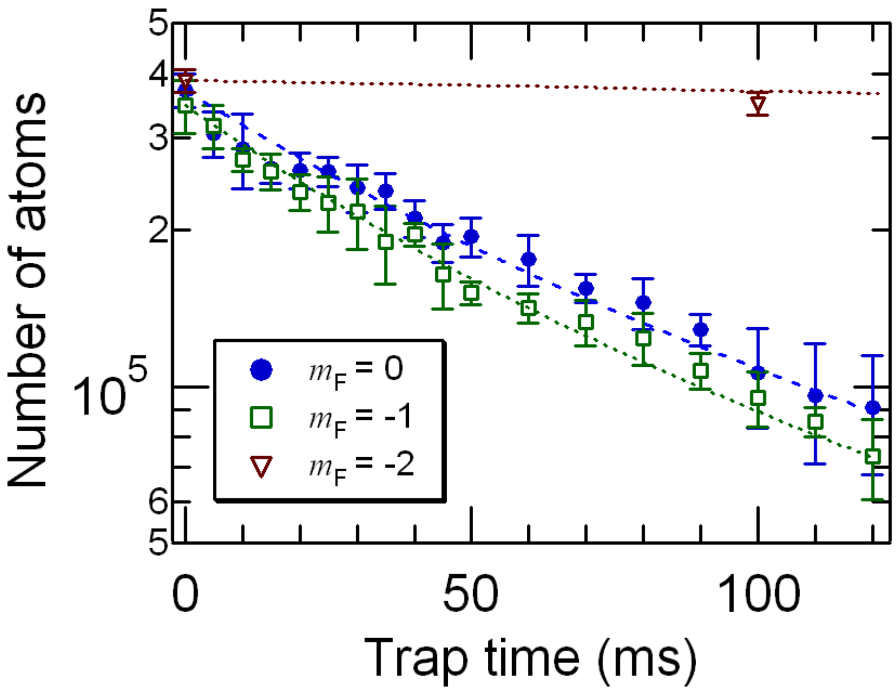
Inelastic collision rates between spin-states

Total spin of collision channel:
▯ = 0, 2, 4

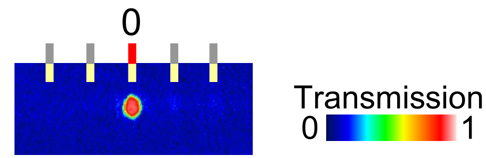
By analogy with the scattering length in elastic collisions, two-body inelastic collisions are described by two parameters, b_0 and b_2, which correspond to channels with the total spins of 0 and 2, respectively.

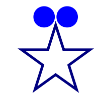


Atom number evolution : single component



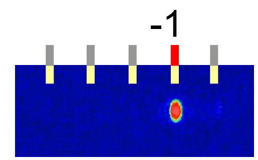
m_F= 0 & 0

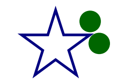




$K_{2(0,0)}$ = (9.7±1.0)×10^{-14} cm^{-3}/s

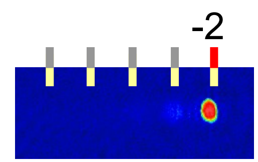
m_F= -1 & -1

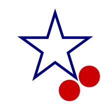




$K_{2(-1,-1)}$ = (11.3±1.1)×10^{-14} cm^{-3}/s

m_F= -2 & -2





($K_{2(-2,-2)}$ = (0.46±0.05)×10^{-14} cm^{-3}/s)

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

  ⇨ Negligible inelastic collision for m_F= -2, -2 (stretched state)

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

Two body inelastic collision : b_0, b_2

- Relation between m_1, m_2 and b_0, b_2

$$K_{m1,m2} \sim b_2 \left| \langle \langle 2, m_1 + m_2 || 2, m_2 \rangle | 2, m_1 \rangle \right|^2 + b_0 \left| \langle \langle 0, m_1 + m_2 || 2, m_2 \rangle | 2, m_1 \rangle \right|^2$$

m_F= 0 & 0 $\quad |2,0\rangle|2,0\rangle = \sqrt{\frac{18}{35}}||4,0\rangle\rangle - \sqrt{\frac{2}{7}}||2,0\rangle\rangle + \sqrt{\frac{1}{5}}||0,0\rangle\rangle$

$$\Rightarrow K_{0,0} = \frac{2}{7} b_2 + \frac{1}{5} b_0$$

m_F= -1 & -1 $\quad |2,-1\rangle|2,-1\rangle = \sqrt{\frac{4}{7}}||4,-2\rangle\rangle - \sqrt{\frac{3}{7}}||2,-2\rangle\rangle$

$$\Rightarrow K_{-1,-1} = \frac{3}{7} b_2$$

m_F= -2 & -2 $\quad |2,-2\rangle|2,-2\rangle = ||4,-4\rangle\rangle$

$$\Rightarrow K_{-2,-2} = 0$$

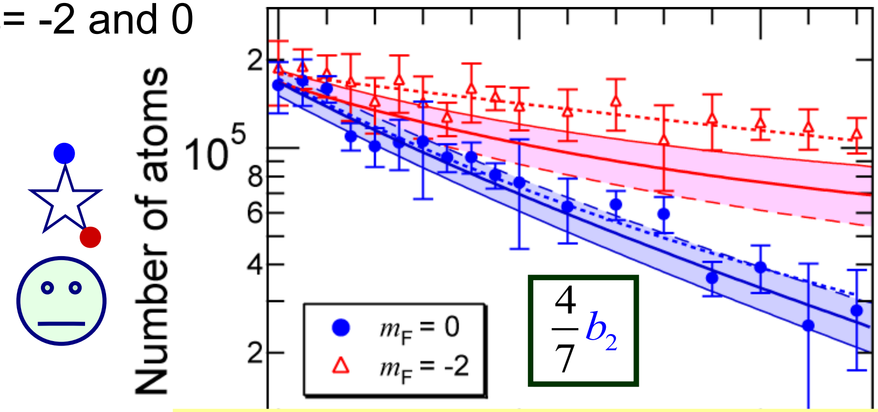
Evaluation of b_2, b_0

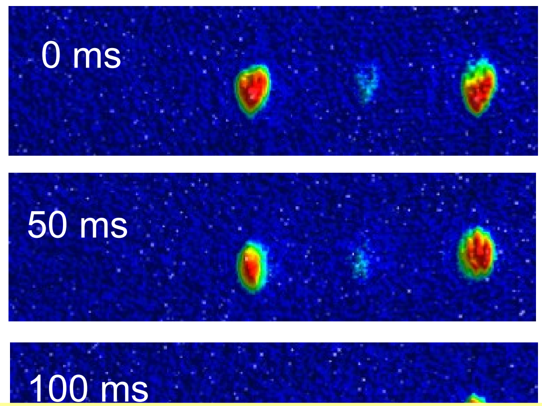
b_0 = (11.1±6.1)×10^{-14} cm^{-3}/s

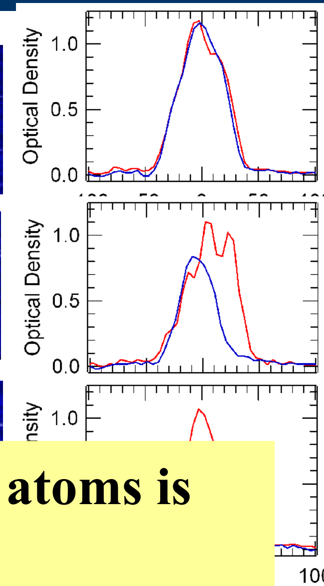
b_2 = (26.3±2.7)×10^{-14} cm^{-3}/s

Atom number evolution : m_F = -2,0 and m_F = -1,0

m_F= -2 and 0

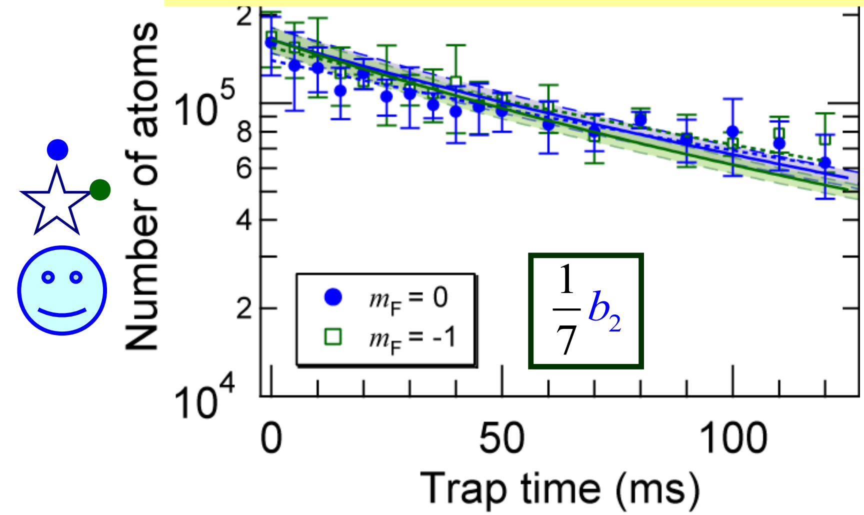


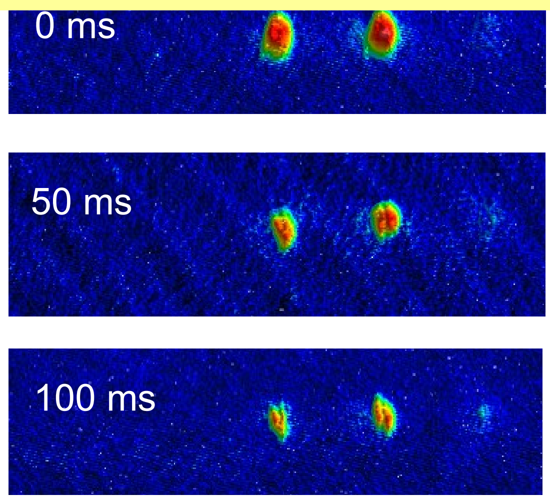




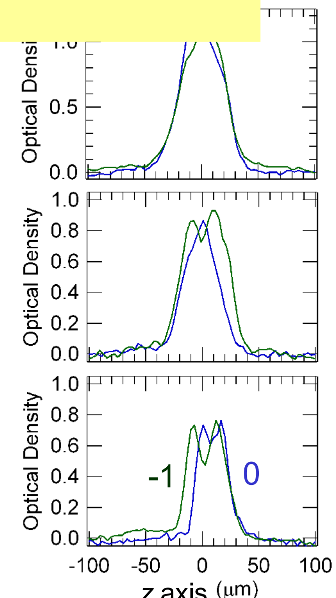
The possibility that the inelastic collision rate of m_F=0 atoms is much higher than that of another states is denied.
→ Diagnostics by saito & ueda should work.

m_F= -1 and



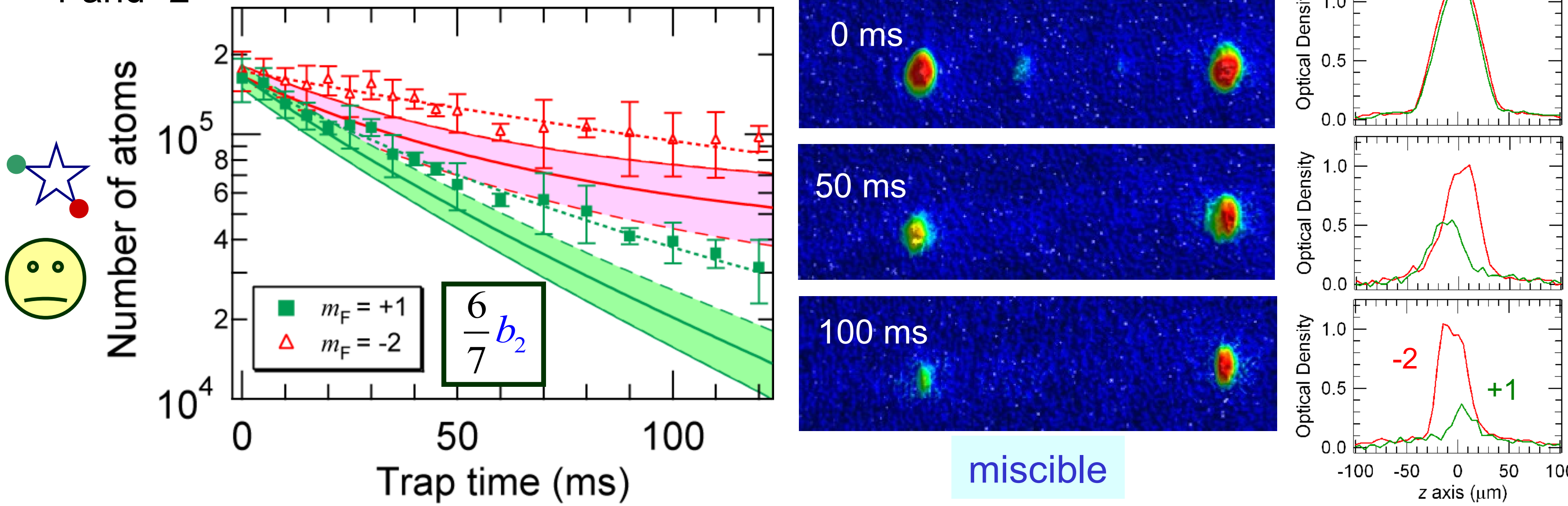


phase separation

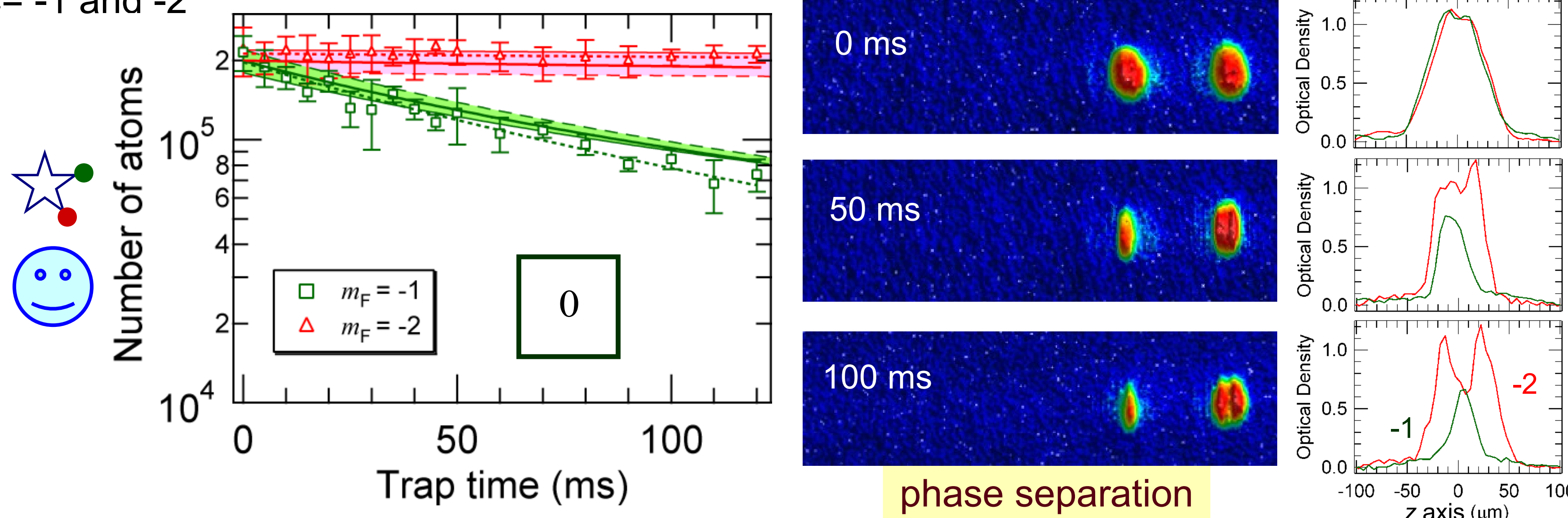


Atom number evolution : m_F = +1,-2 and m_F = -1,-2

m_F= +1 and -2

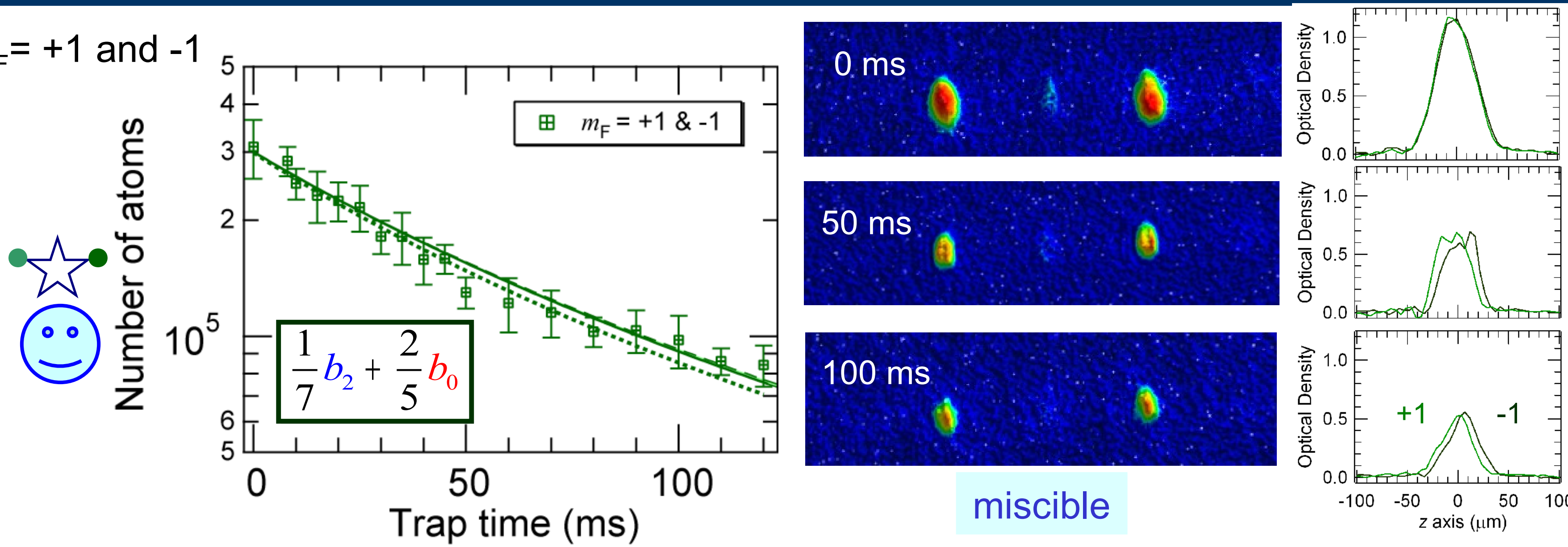


m_F= -1 and -2

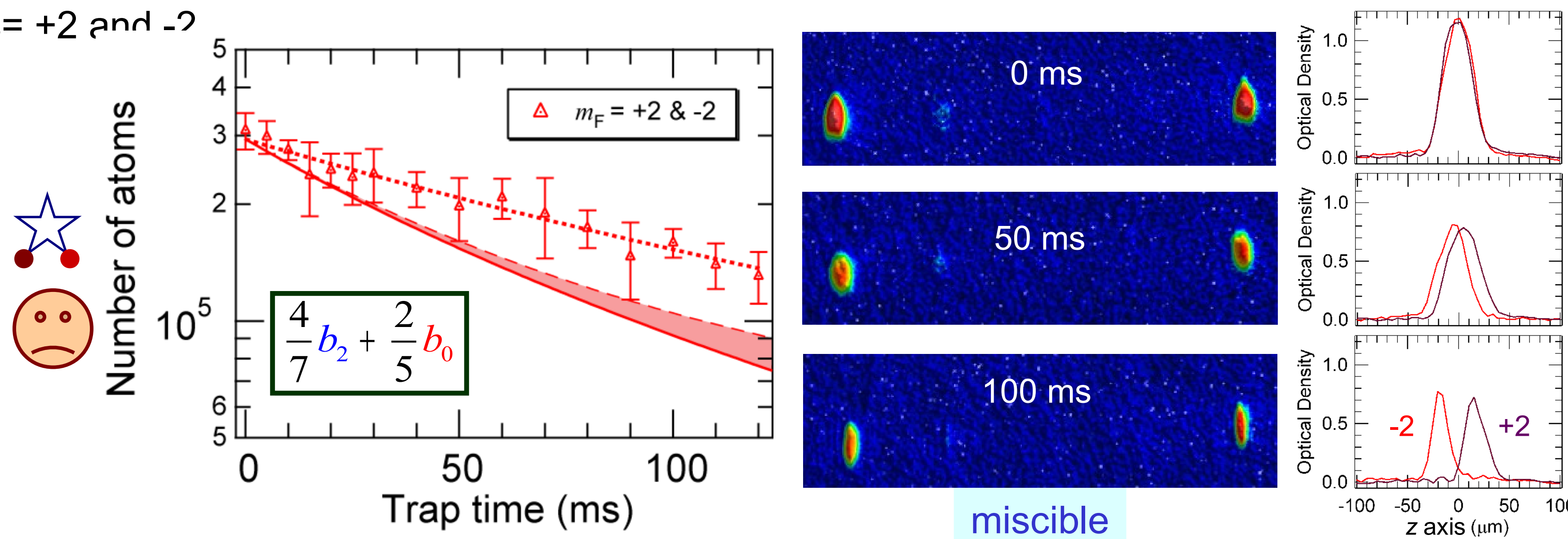


Atom number evolution : m_F = +1,-1 and m_F = +2,-2

m_F= +1 and -1

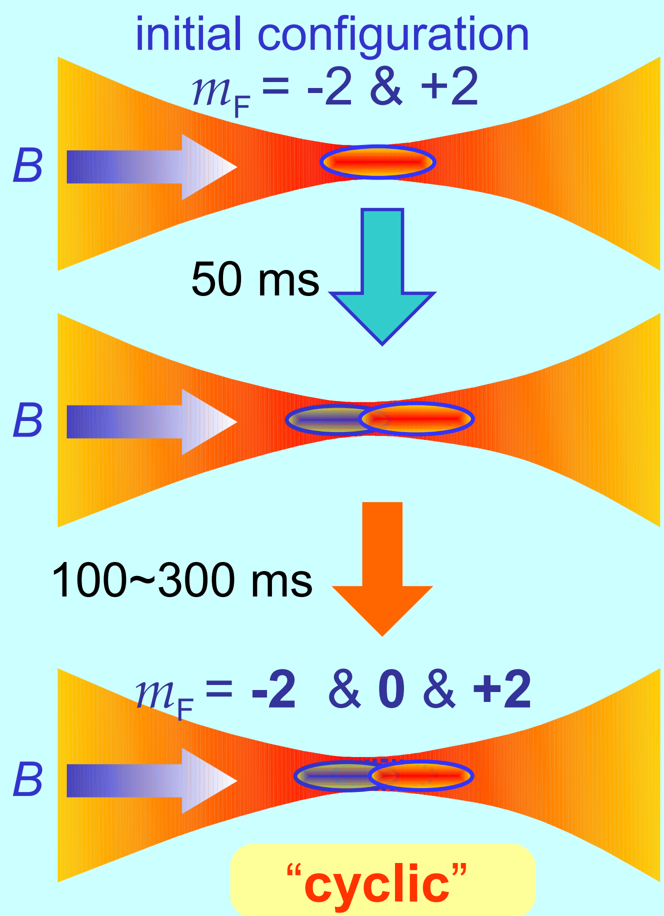


m_F= +2 and -2



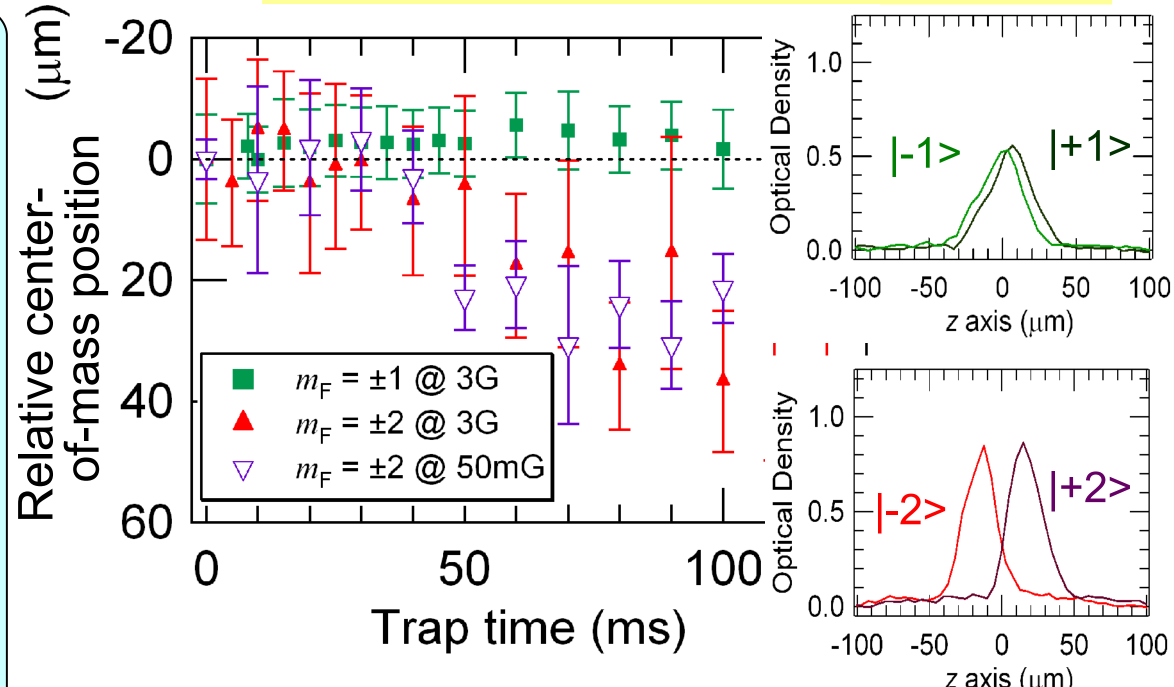
Problem-2: Relative center-of-mass positions between m_F = +2 & -2

Spin population



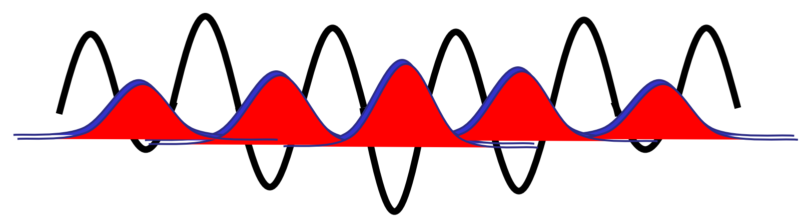
Relative displacement prevents production of m_F = 0 state in cyclic.

Relative center of mass position



Displacement may be due to magnetic field gradient.

Displacement can be suppressed in 1D optical lattice



Summary

^{87}Rb BEC with internal degrees of freedom

- Magnetic sublevels can be coherently coupled, and their populations can be controlled.
- Scattering lengths can be controlled by Feshbach Reaonance.

Controlling phase-separation behavior of two-component BEC

- The scattering length is obtained by comparing the shape of the atomic cloud by comparison with the numerical analysis.

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

$b_2 = (11.1 \pm 1.1) \times 10^{-13}$ cm^3/s, $b_0 = (26.3 \pm 2.7) \times 10^{-13}$ cm^3/s

Ground-state phase of F=2 ^{87}Rb BEC

- Results supported anti-ferromagnetic(but several problems).
- We solved two problems: inelastic collision and spatial separation

  → Preliminary results reported by Tanabe: P86