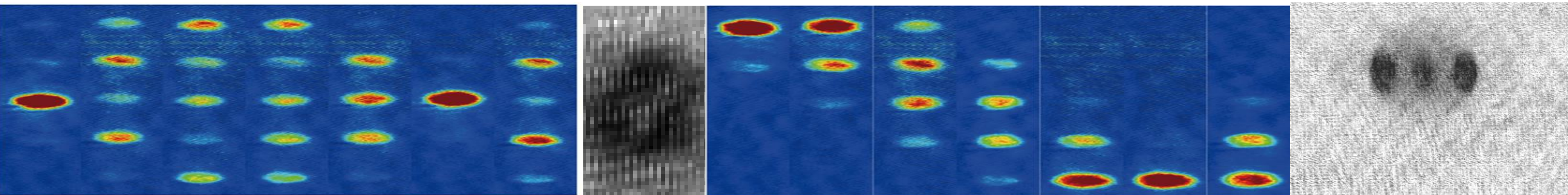
「量子クラスターで読み解く物質の階層構造」キックオフシンポジウム
2018年11月19日(月)　東京工業大学大岡山キャンパス

学習院大学
GAKUSHUIN UNIVERSITY

極低温原子集団における散逸と状態変化の普遍性

学習院大学理学部物理学科

平野 琢也



Overview of our group

Members	**Hirano, Takuya**	**Professor, Gakushuin Univ.**	**Experiment**
	Eto, Yujiro	**AIST, Japan**	**Experiment**
	Kosukei, Shibata	**Assist. Prof., Gakushuin Univ.**	**Experiment**
	Takahashi, Masahiro	**Assist. Prof., Gakushuin Univ.**	**Theory**
	Saito, Hiroki	**Professor, UEC**	**Theory**

自己紹介

１９８７年３月　東京大学理学部物理学科卒業

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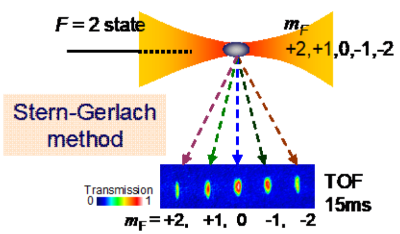
2004年9月 -2006年8月 日本物理学会男女共同参画推進委員会委員

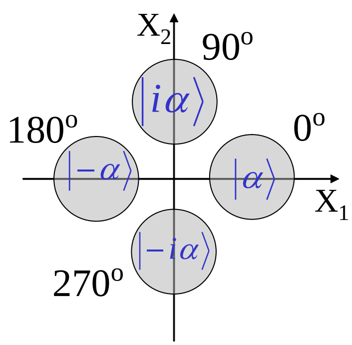
2007年8月 -2009年7月 文部科学省学術調査官

Ｒｂ原子ＢＥＣ,



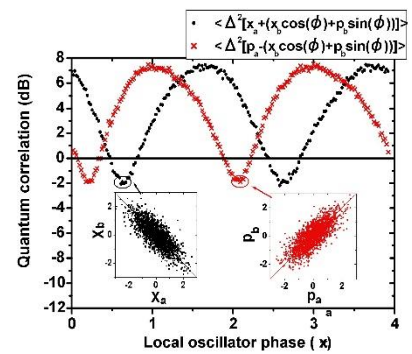
多成分凝縮体の非平衡現象の解明

連続量量子暗号,



コヒーレント光通信との統合

パルス光スクイージング

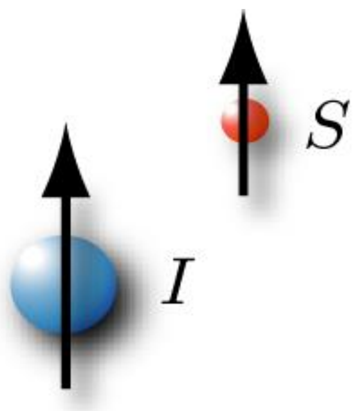


ループホールの無いＥＰＲ実験
通信・情報処理への展開

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 unstable
^{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)

All spin states can be trapped in an optical trap

Novel physics in quantum fluids with many internal degrees of freedom

^{87}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	

- Magnetic sublevels can be coherently coupled, and their populations can be controlled.
- Scattering lengths can be controlled via Feshbach Resonance.
- Rich variety of non-equilibrium dynamics are expected.

  relaxation in an isolated quantum system

  quantum fluctuations : spin-nematic squeezing

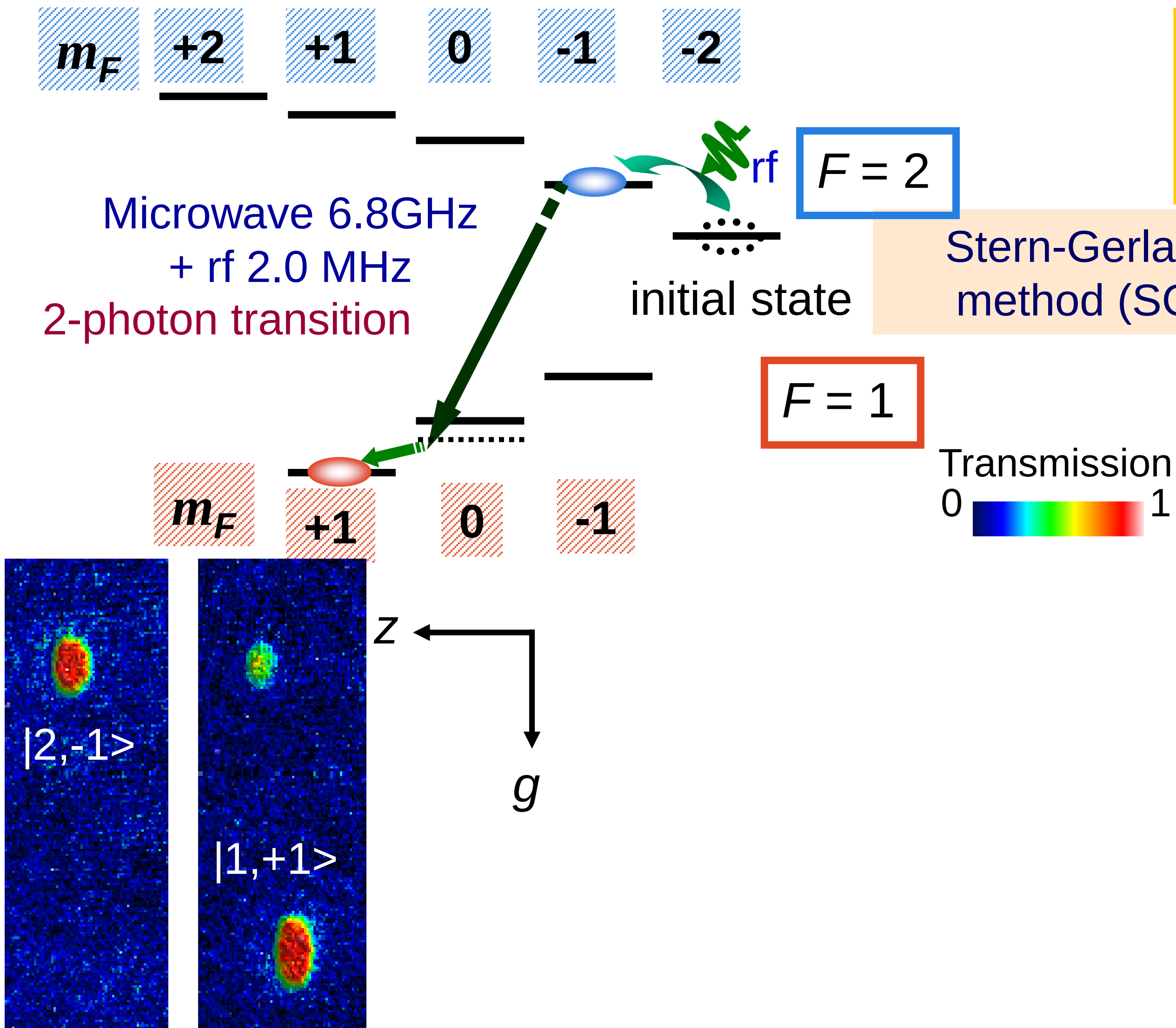
  quantum turbulence, quantum vortex dynamics,

  phase separation, interface of different components

  spin dynamics, etc…

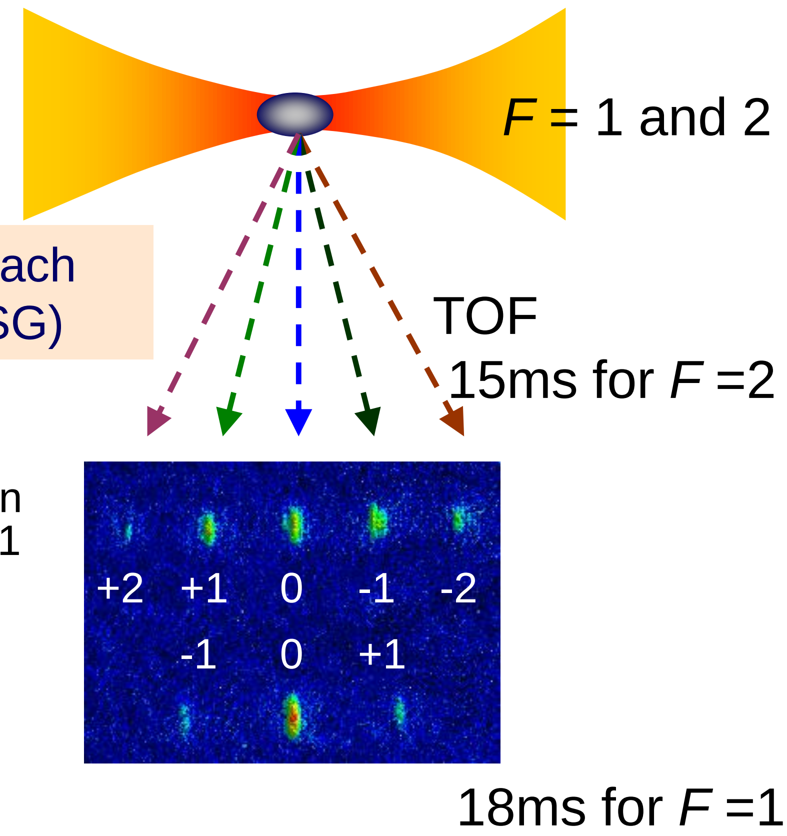
State manipulation

Energy level diagram of ^{87}Rb at 20 G



Stern-Gerlach method (SG)

Time evolution and imaging



Collisions in Spin-2 spinor BEC

elastic : spin-exchange collision

before **after**

$$|2, m_1\rangle + |2, m_2\rangle \rightarrow |2\ m_3\rangle + |F, m_4\rangle$$

$$m_1 + m_2 = m_3 + m_4$$

ex. $|2, 0\rangle + |2, 0\rangle \leftrightarrow |2, +1\rangle + |2, -1\rangle$

coherent evolution between ***m_F***

inelastic : hyper-fine changing collision

before **after**

$$|2, m_1\rangle + |2, m_2\rangle \rightarrow |1, m_3\rangle + |F, m_4\rangle$$

ex.

$|2, 0\rangle + |2, 0\rangle \rightarrow |1, +1\rangle + |2, -1\rangle$

$\rightarrow$ **two-body loss**

Impossible: $|2, 2\rangle + |2, 2\rangle \rightarrow |1, m_3\rangle + |F, m_4\rangle$

m_F dependent loss

S. Tojo, *et al.*, PRA 80, 042704 (2009).

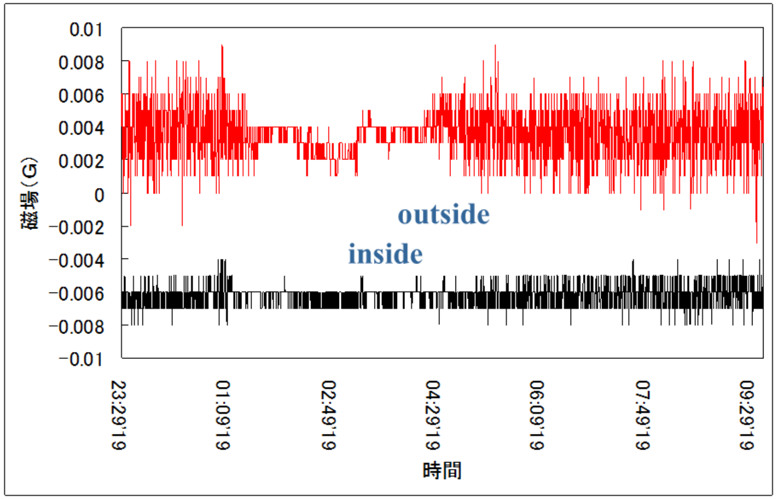
spontaneous symmetry breaking and self-organized coherence formation in a dissipative quantum system

Experimental techniques

State-of-the-art spin manipulation technique

①. High fidelity initial-state preparation

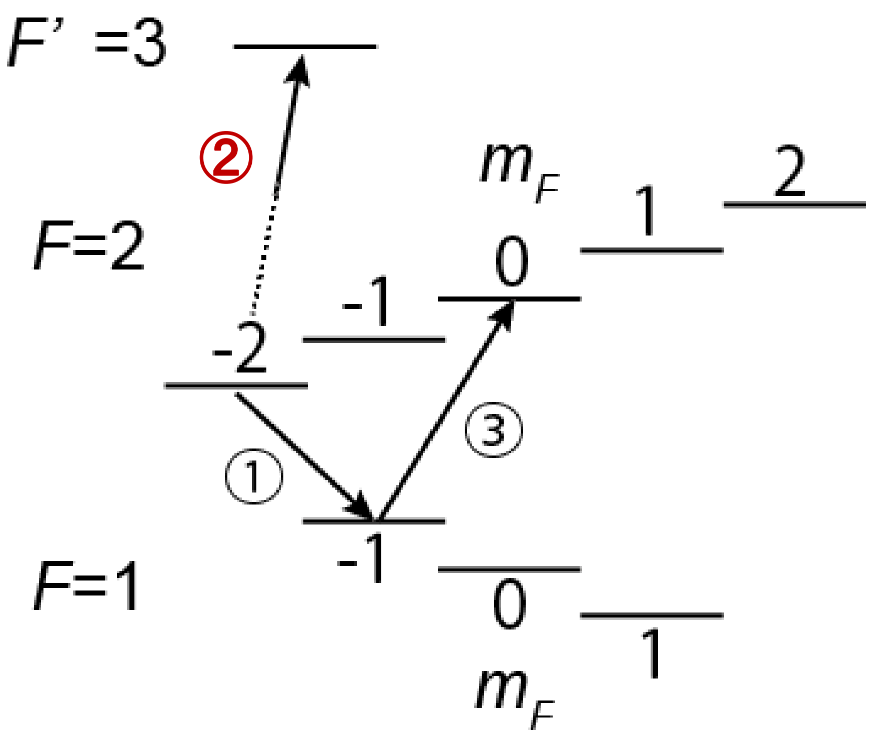
②. Stern-Gerlach measurement with precise spin rotation by application of rf pulses



BEC machine in a magnetic shield room

High fidelity initial-state preparation

Experimental procedure



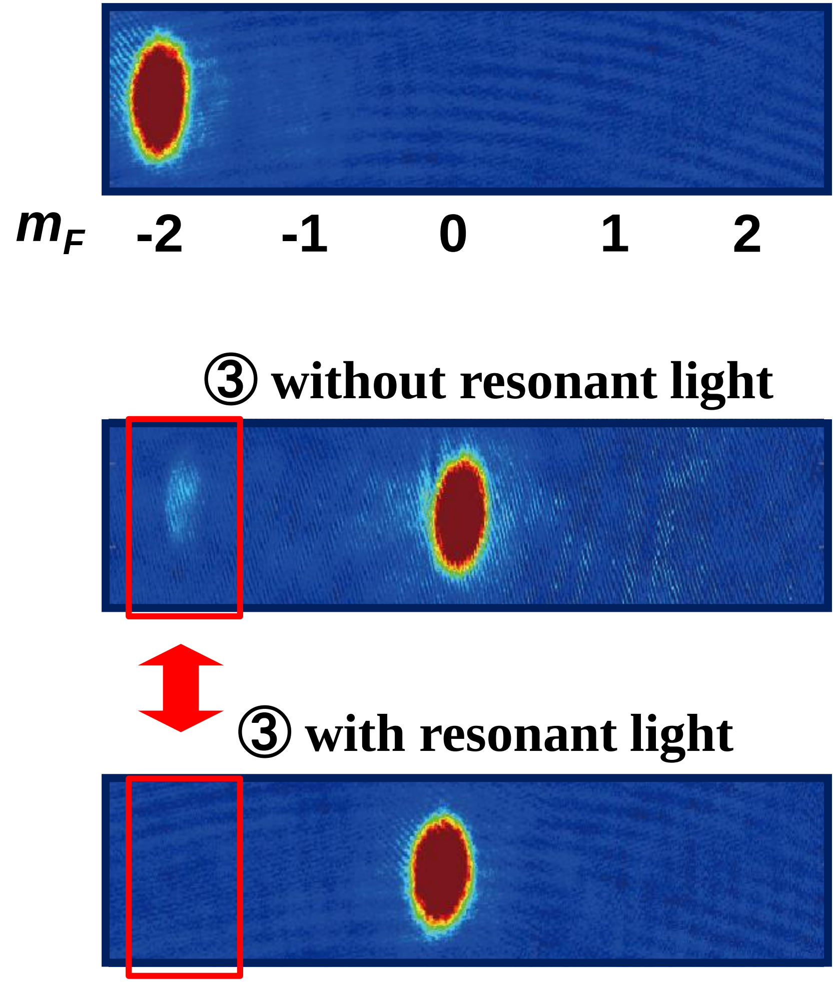
bias mag. field : 200mG

microwave ① **: 6.834264565 GHz**

③ **: 6.834542658 GHz**

resonant. light ② **: 780.24 nm**

Before microwave irradiation

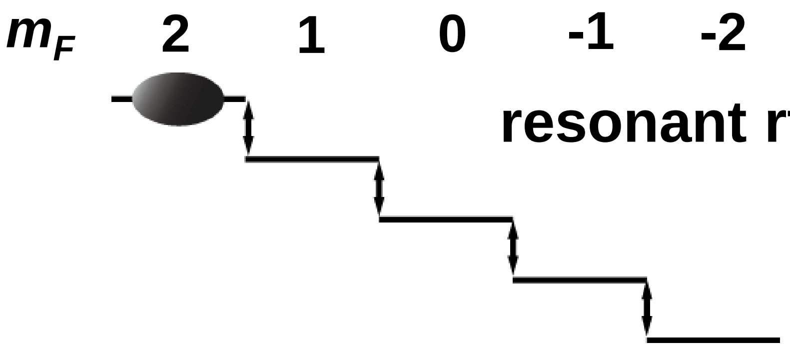


Pure initial state

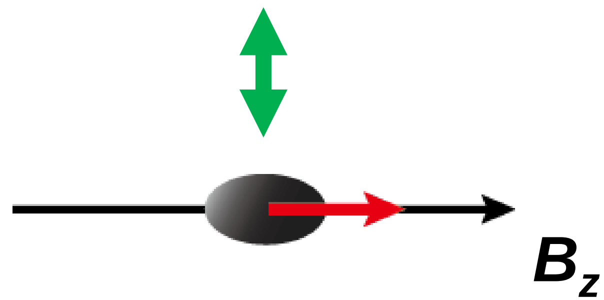
spin rotation by rf pulse

If magnetic field is sufficiently low Zeeman shift is linear.

Spin state rotation resonant rf pulse

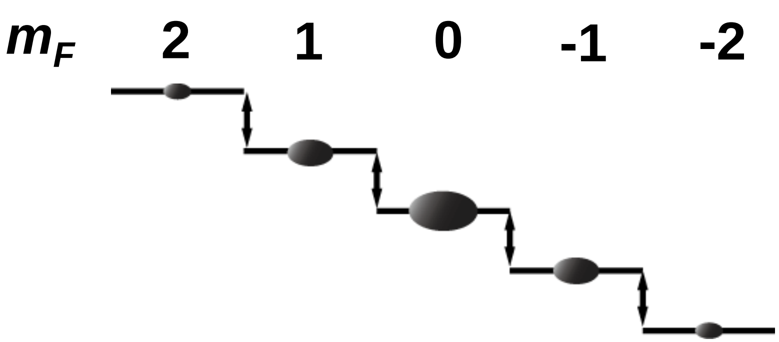


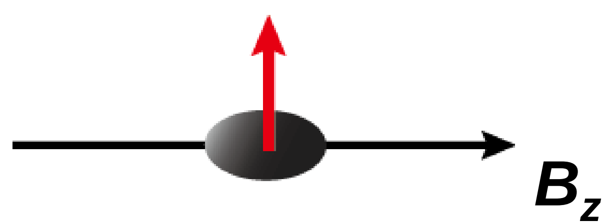
resonant rf pulse



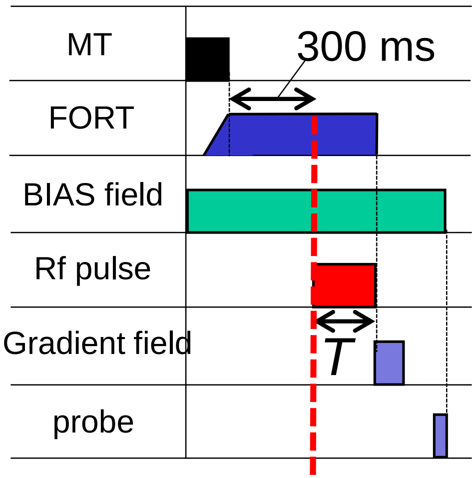
Quantization axis along bias magnetic field

After rf pulse

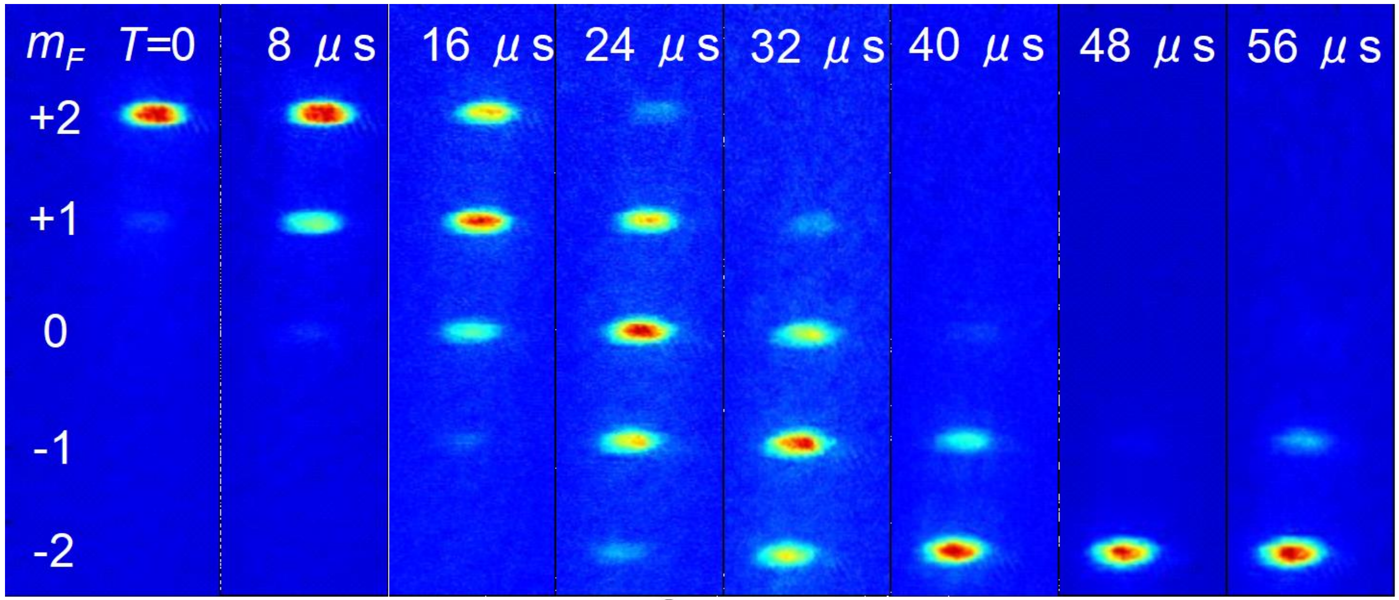




Spin rotation by rf pulse @B_z=34.4 mG



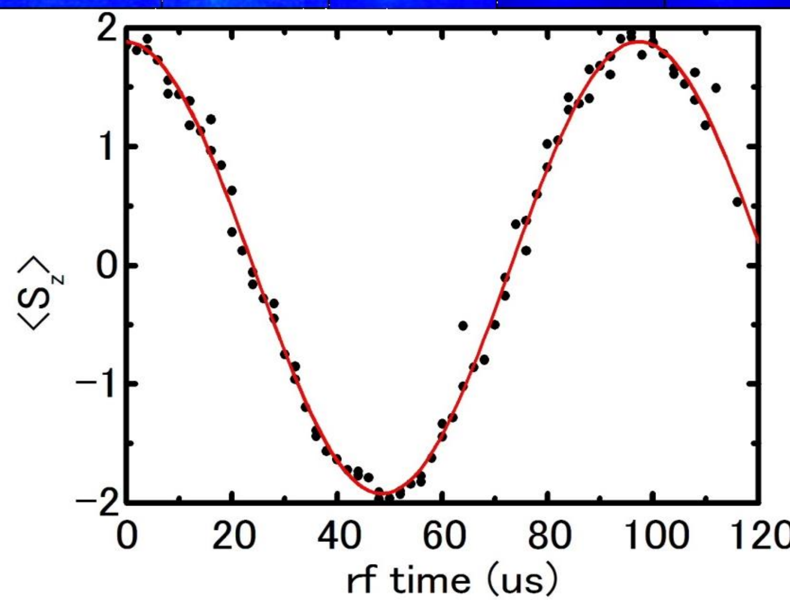
Initial state
m_F=+2



Spin z-component

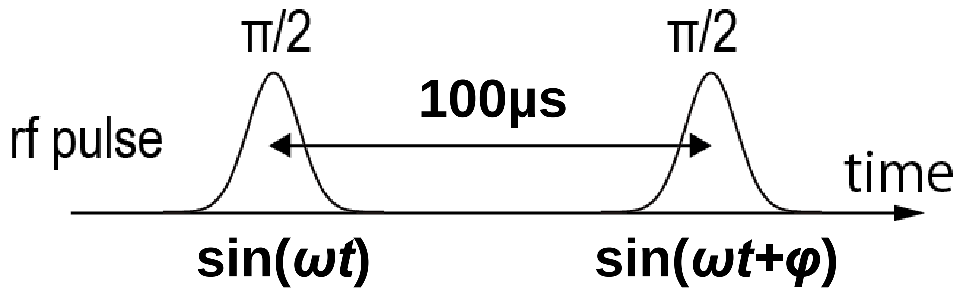
$$\langle S_z \rangle = \sum_{m_F=-2}^{+2} m_F N_{m_F} / N_{\mathrm{total}}$$

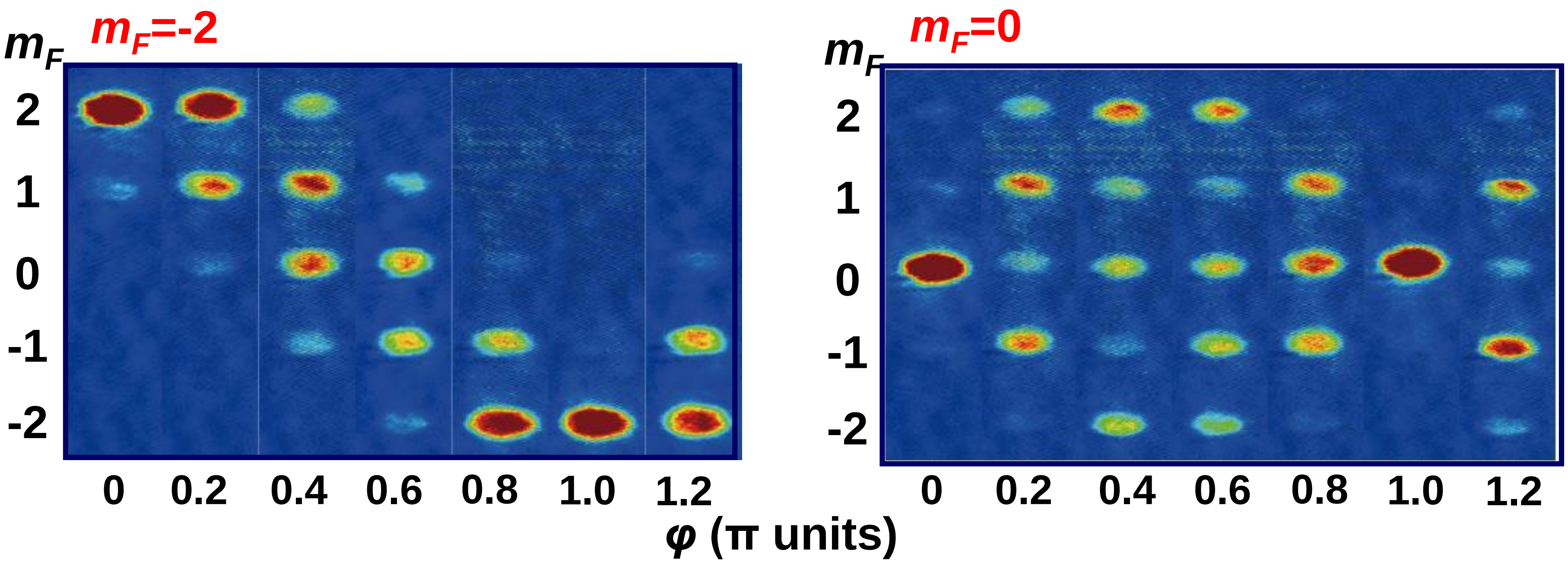
N_{mF} : m_F atom numer
N_{total} : total atom number



spin rotation by rf pulse

Application of two π /2 pulses





Stern-Gerlach measurement with spin rotation by rf pulse

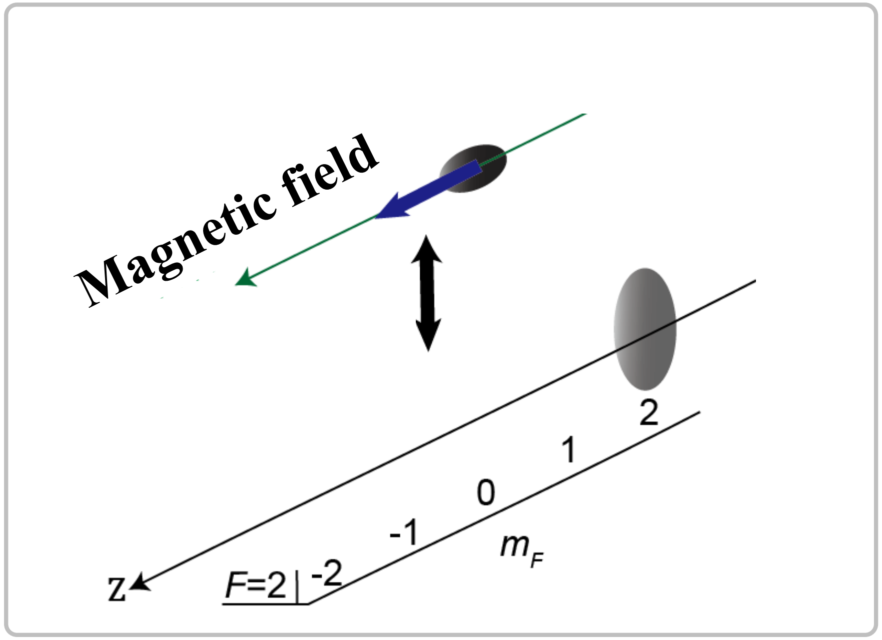
Application of π/2 pulse before Stern-Gerlach sepation

⬇

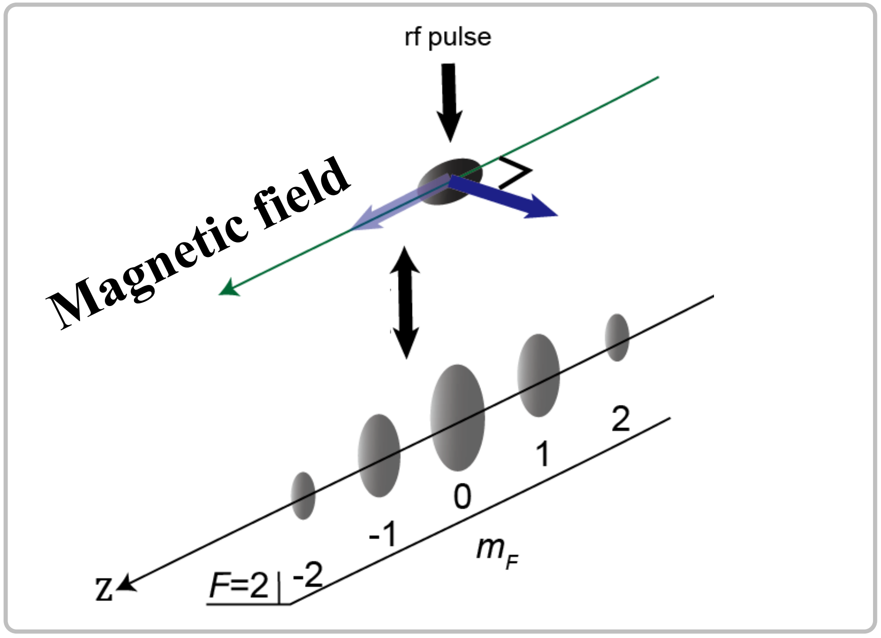
Spin states are rotated by 90 degree.

⬇

We can effectively rotate the measurement axis.



without π/2 rf

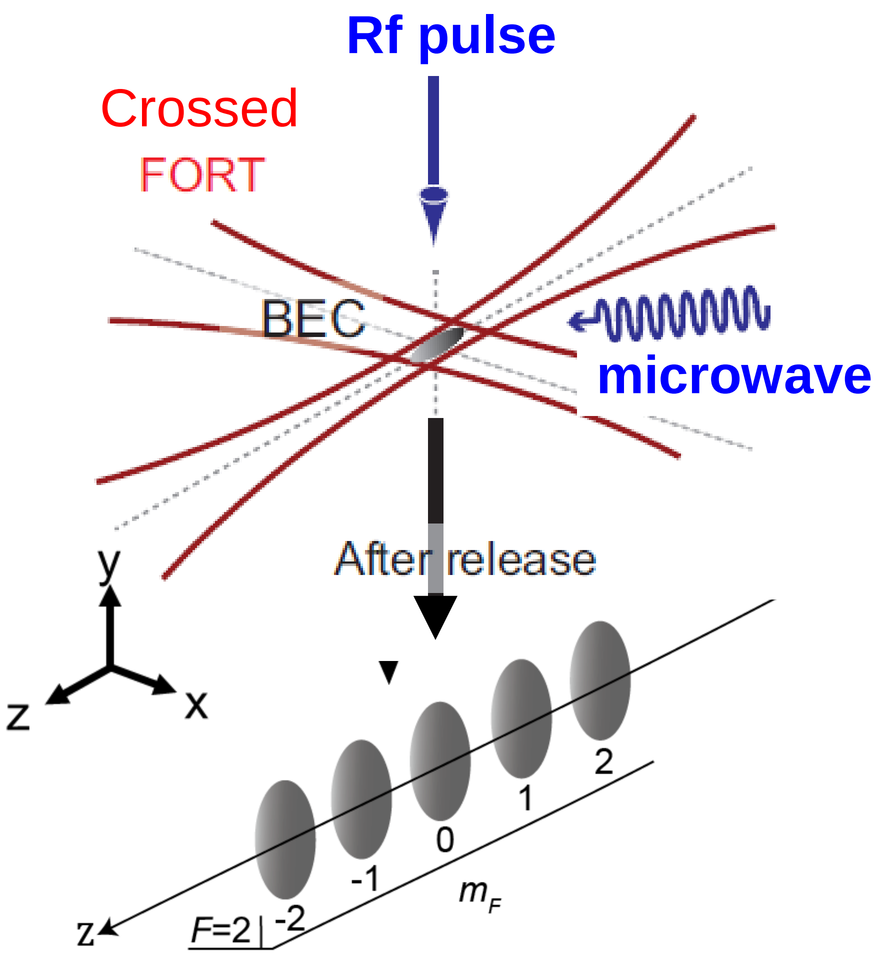


with π/2 rf

Experimental procedures

Trap frequency
axial: 64Hz
radial: 180Hz

Bias magnetic field
B_z=200mG



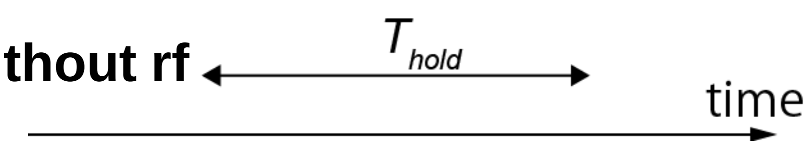
① Creation of BEC in F=2, m_F=-2 state
number of atoms: 3×10^5

② Preparation of F=2, m_F=0 BEC

③ m_F population measurement

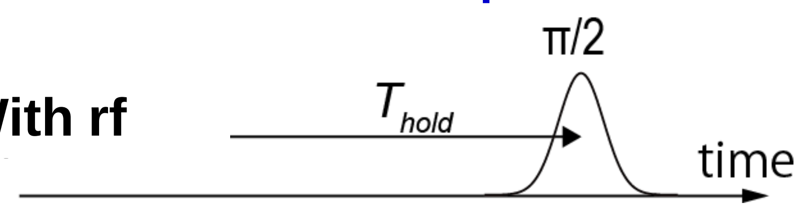
After time evolution of T_{hold}, Stern-Gerlach measurement is performed with and without π/2 rf pulse

(a) Without rf



Measurement axis is parallel to bias

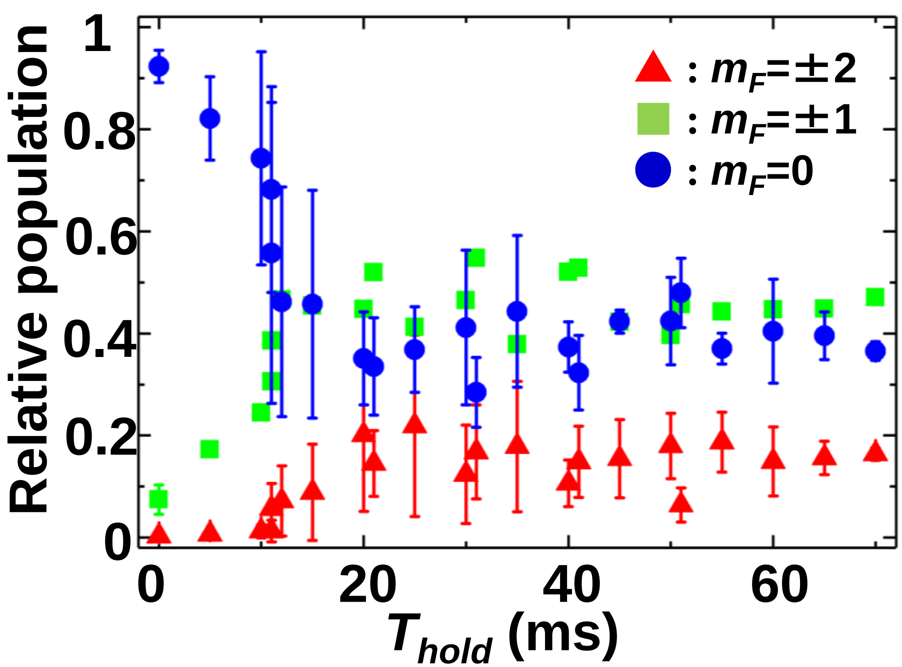
(b) With rf



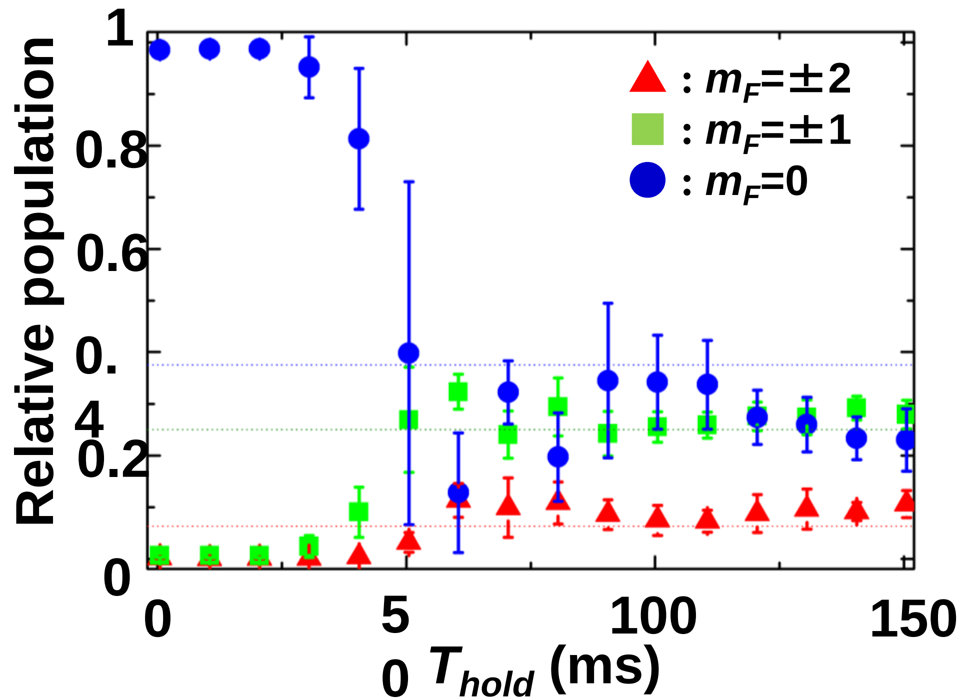
Measurement axis is perpendicular to bias

Evolution of m_F=0 state : measurement axis parallel to mag. field

Mixed initial state (w/o light)



Pure initial state (with light)

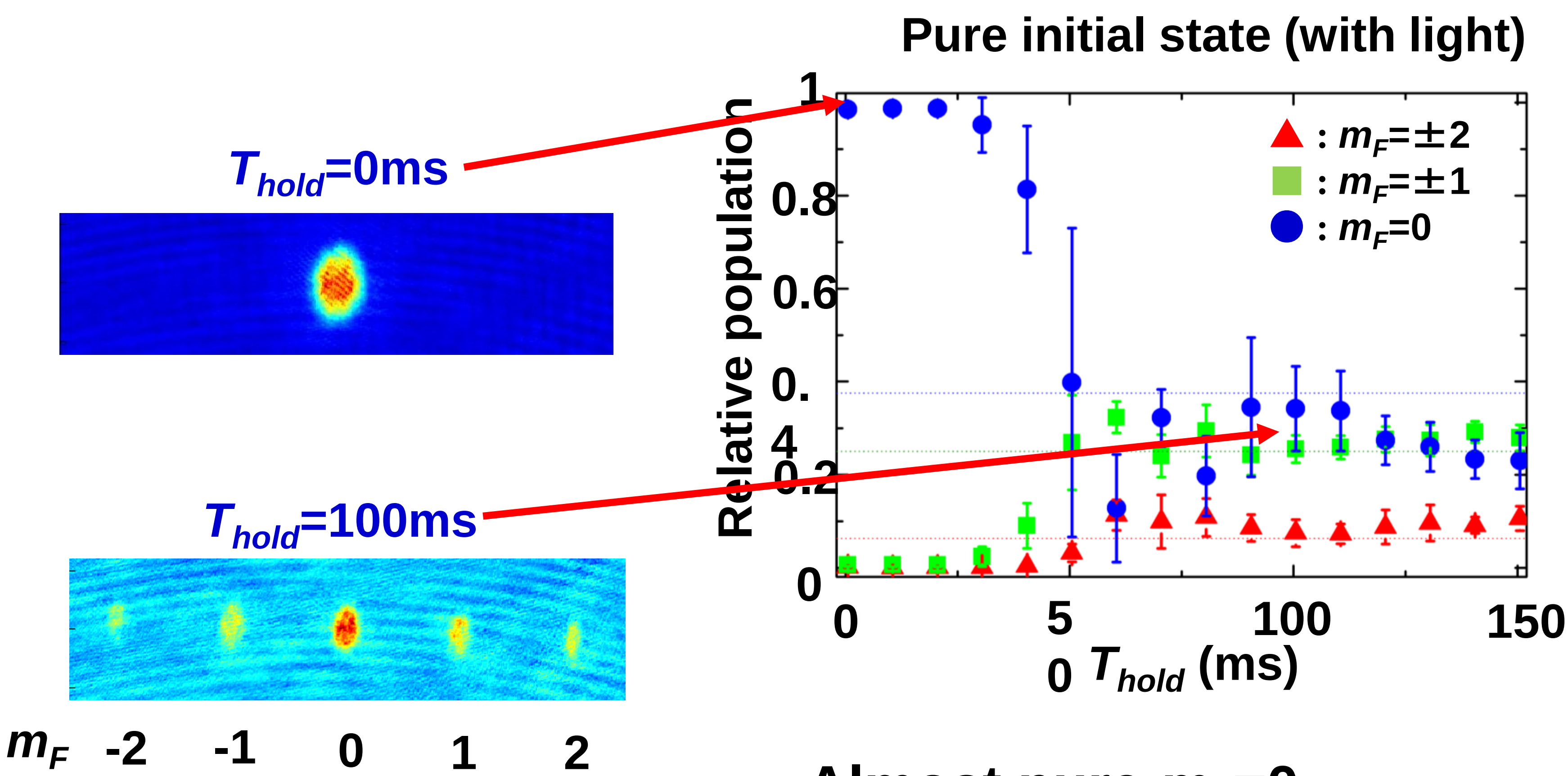


- **ratio of m_F=0 is 0.9 @0ms**
- **rapid decrease even @10ms**

- **Almost pure m_F=0**
- **remains in m_F=0 up to 30ms**

m_F=0 is a quasi-stable state

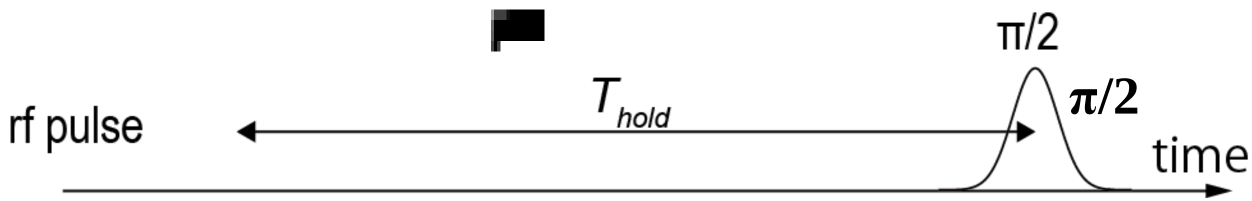
Evolution of m_F=0 state : measurement axis parallel to mag. field



- **Almost pure m_F=0**
- **remains in m_F=0 up to 30ms**

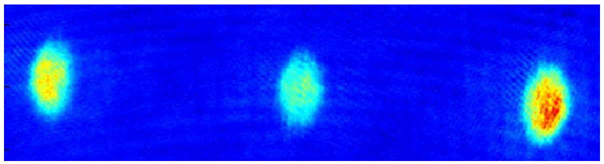
m_F=0 is a quasi-stable state

Evolution of m_F=0 state : meas. axis perpendicular to mag. field



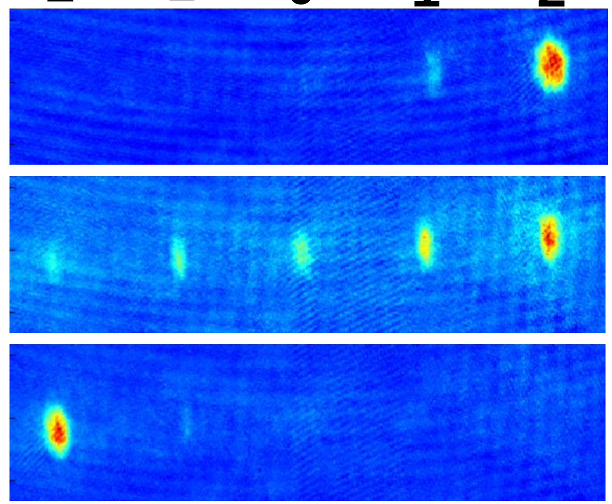
T_{hold}=0ms

m_F -2 -1 0 1 2



T_{hold}=100ms

m_F -2 -1 0 1 2



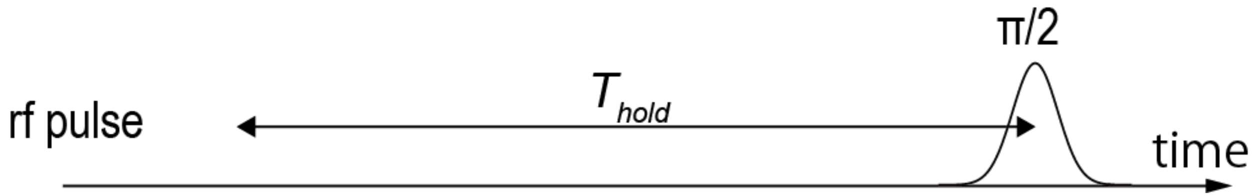
$$|0\rangle_z = \sqrt{\frac{3}{8}}|2\rangle_x + \frac{1}{2}|0\rangle_x + \sqrt{\frac{3}{8}}|-2\rangle_x$$

subscript refers to quantization axis

$$|m_F\rangle = |2, m_F\rangle$$

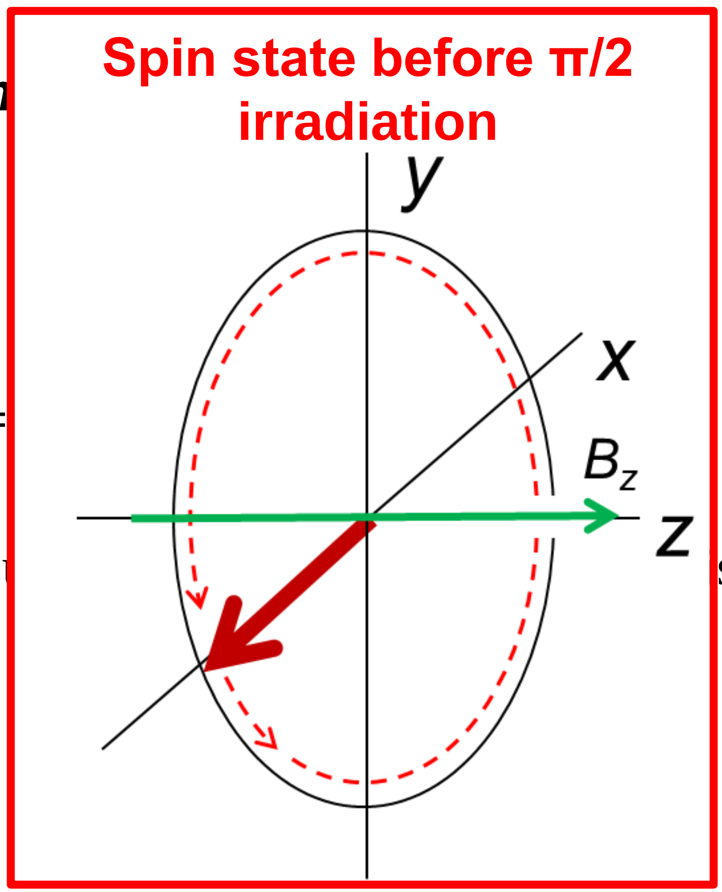
Results were different for each measurement under the same experimental condition

Evolution of m_F=0 state : meas. axis perpendicular to mag. field



m

$|0\rangle_z =$



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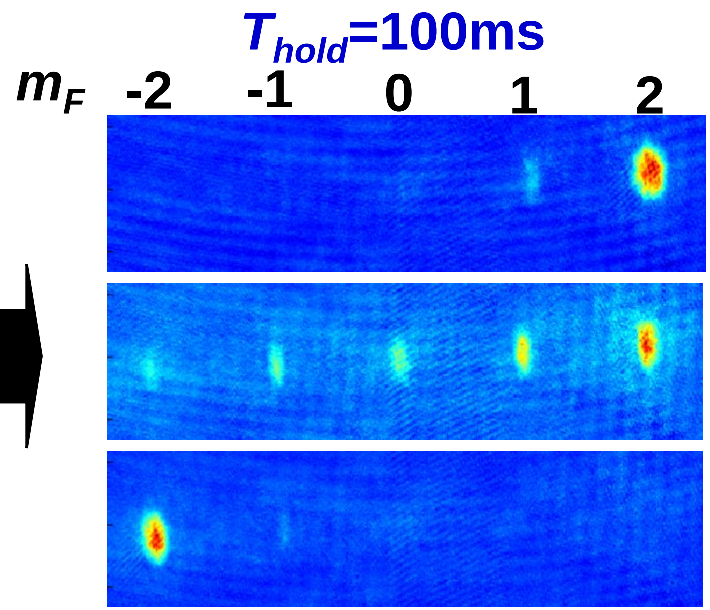
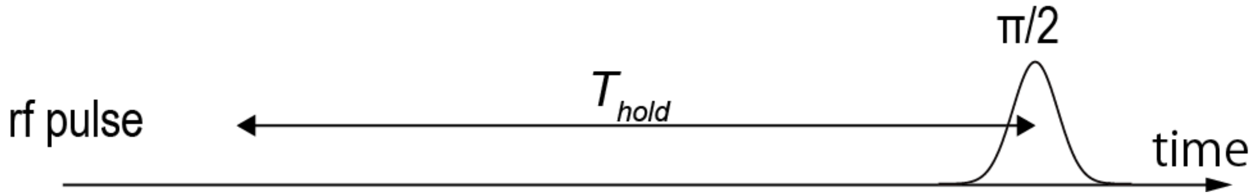
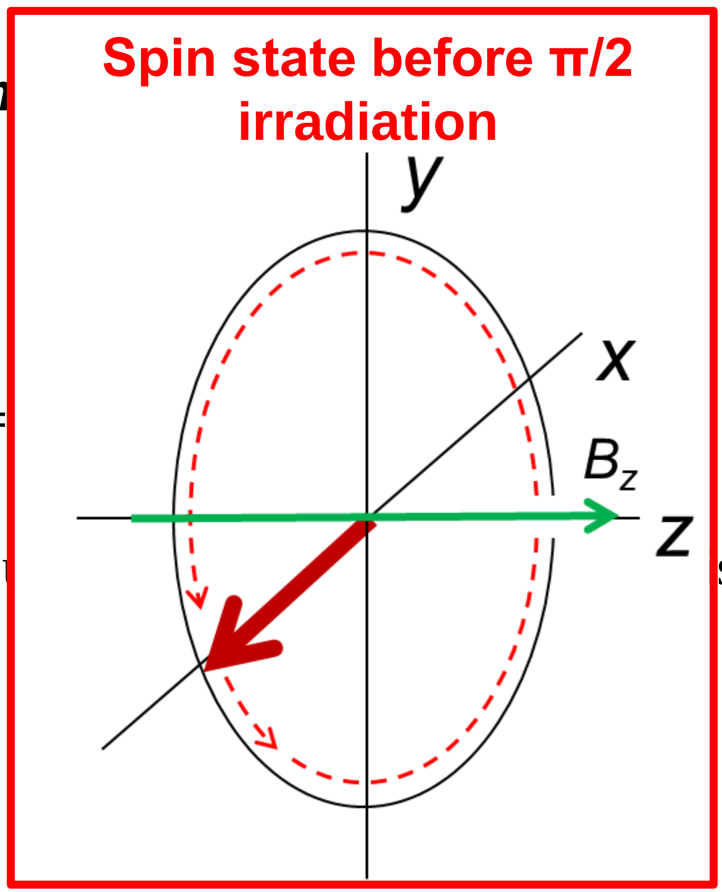


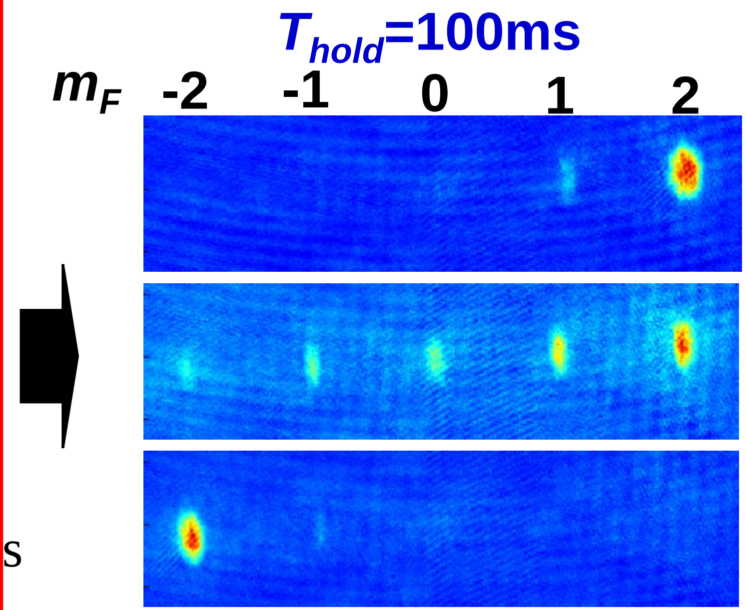
Results were different for each measurement under same experimental condition

Evolution of m_F=0 state : meas. axis perpendicular to mag. field





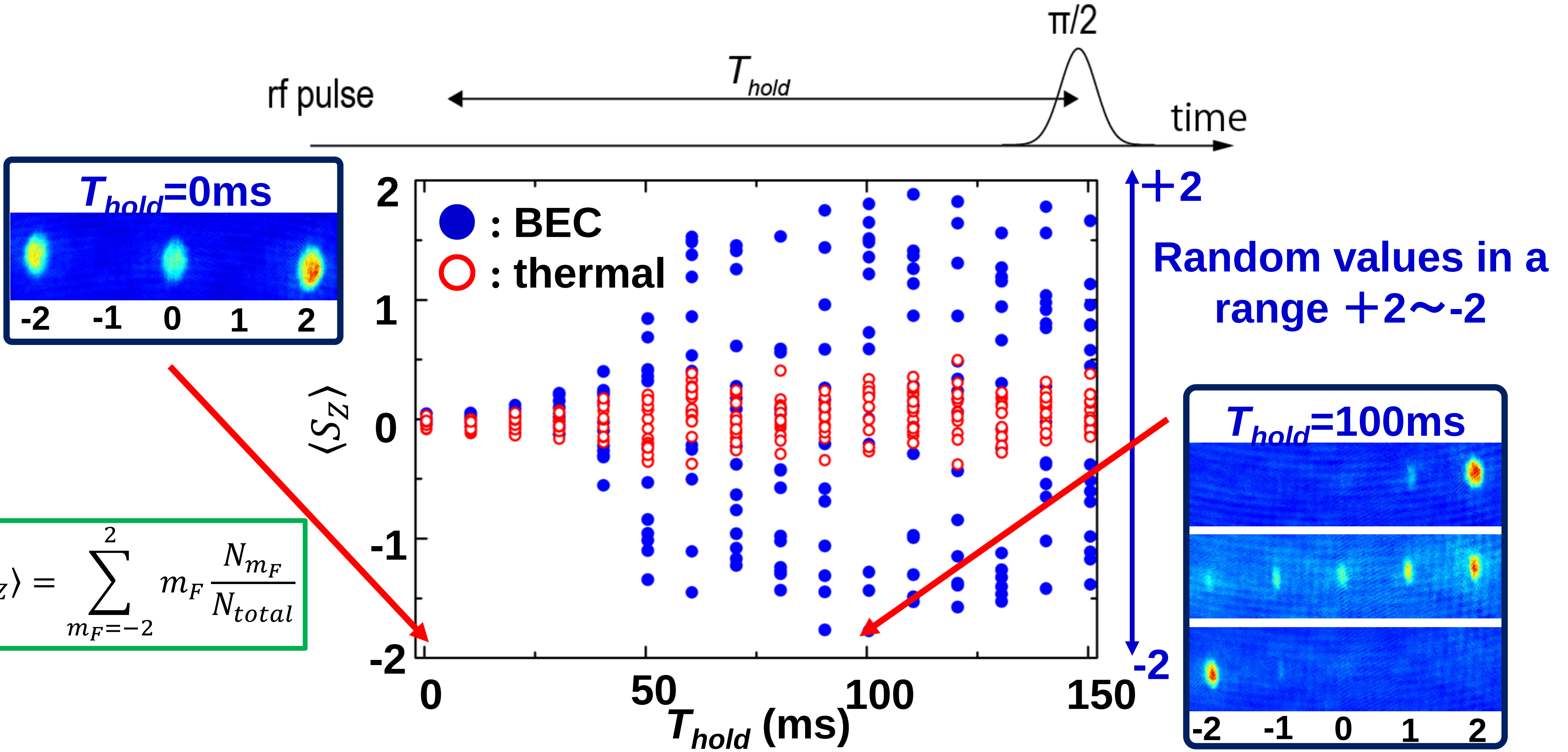
$|0\rangle_z =$



$$\langle S_Z \rangle = \sum_{m_F=-2}^{2} m_F \frac{N_{m_F}}{N_{total}}$$

Expectation value of z-component of spin $\langle S_Z \rangle$

Time evolution of m_F=0 state



$$\langle S_Z \rangle = \sum_{m_F=-2}^{2} m_F \frac{N_{m_F}}{N_{total}}$$

Larmor precession of almost full stretched state along the bias magnetic field at 100ms

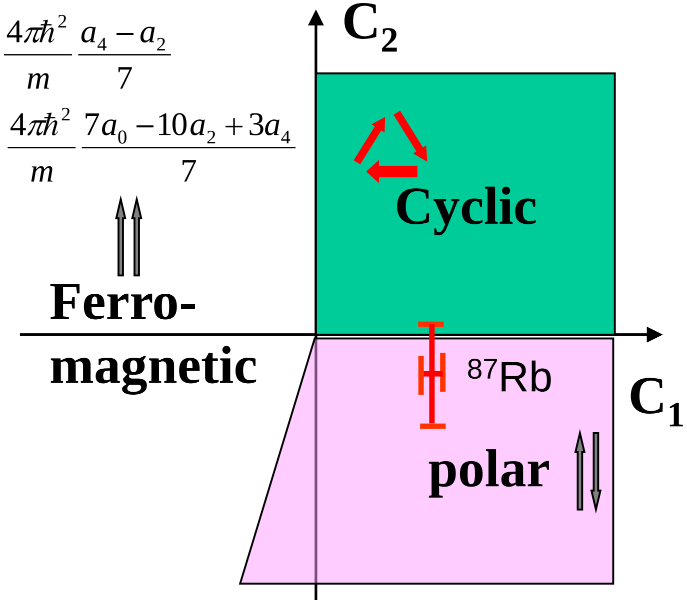
Mechanism for spontaneous magnetization

1. **generation of $m_F = \pm 1$ and $m_F = \pm 2$ states by spin-exchange collision**
2. **m_F dependent loss by hyperfine-changing collision**

→ formation of phase relations between magnetic sub-levels such that the superposed state is spin-polarized perpendicular to the bias field: a spin-polarized state is robust against two-body inelastic loss (hyperfine-changing collision)

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

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



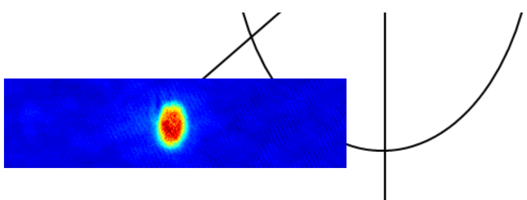
Note that the magnetic ground state of F=2 ^{87}Rb BEC is cyclic or polar.

1. **generation of $m_F = \pm 1$ and $m_F = \pm 2$ states by spin-exchange collision**
2. **m_F dependent loss by hyperfine-changing collision**

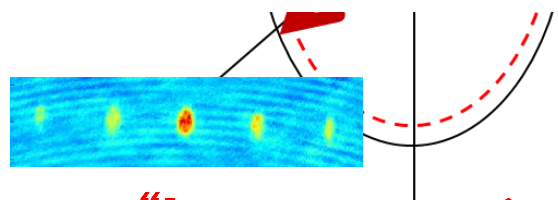
→ spin-polarized state perpendicular to the bias field

spontaneous symmetry breaking and self-organized coherence formation in a dissipative quantum system

Usually, dissipation causes decoherence. In this case, dissipation makes coherence. May give an insight on quantum dynamics in a dissipative system, i.e., why photosynthesis is efficient.

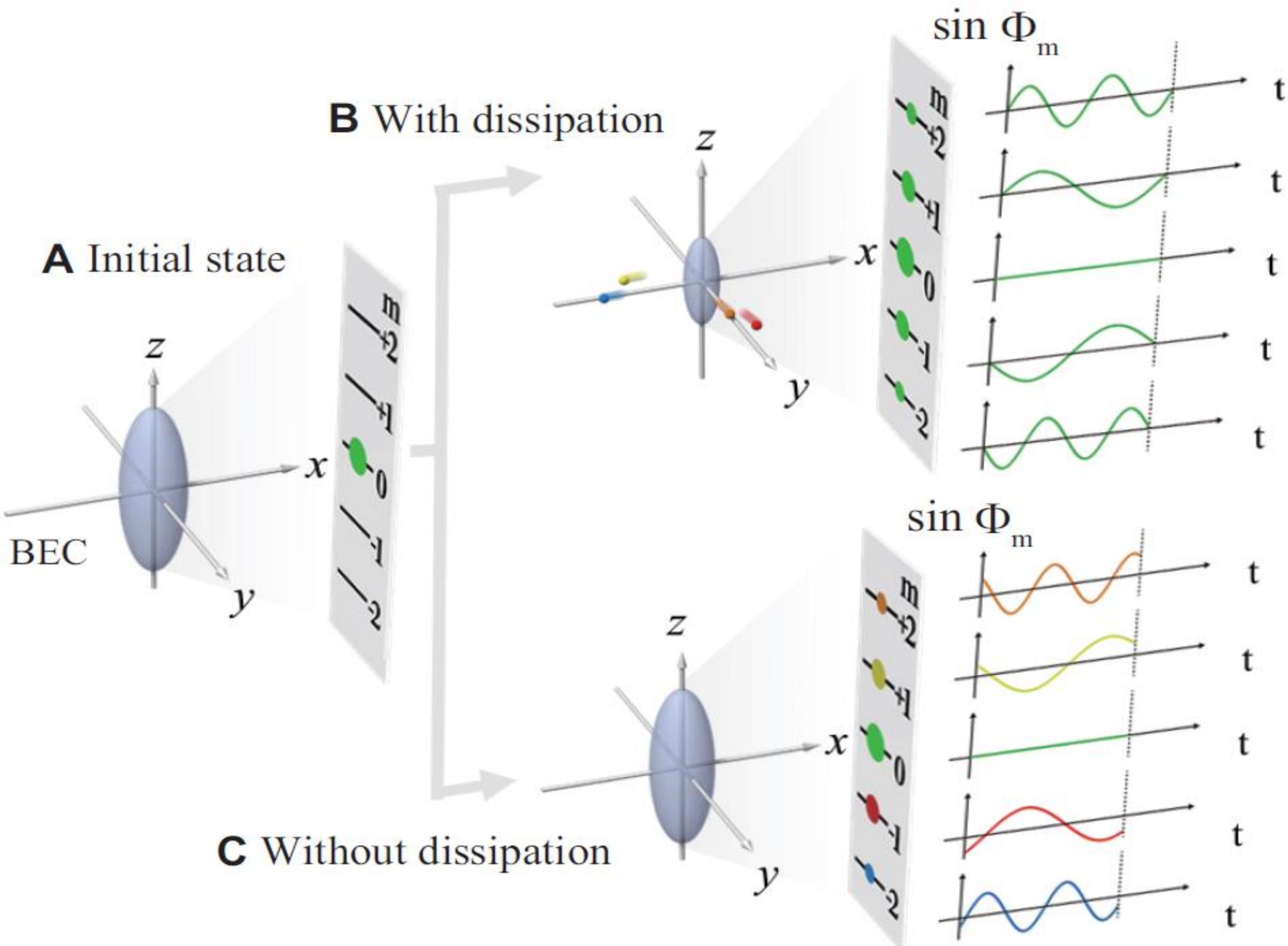


"symmetric around z-axis"

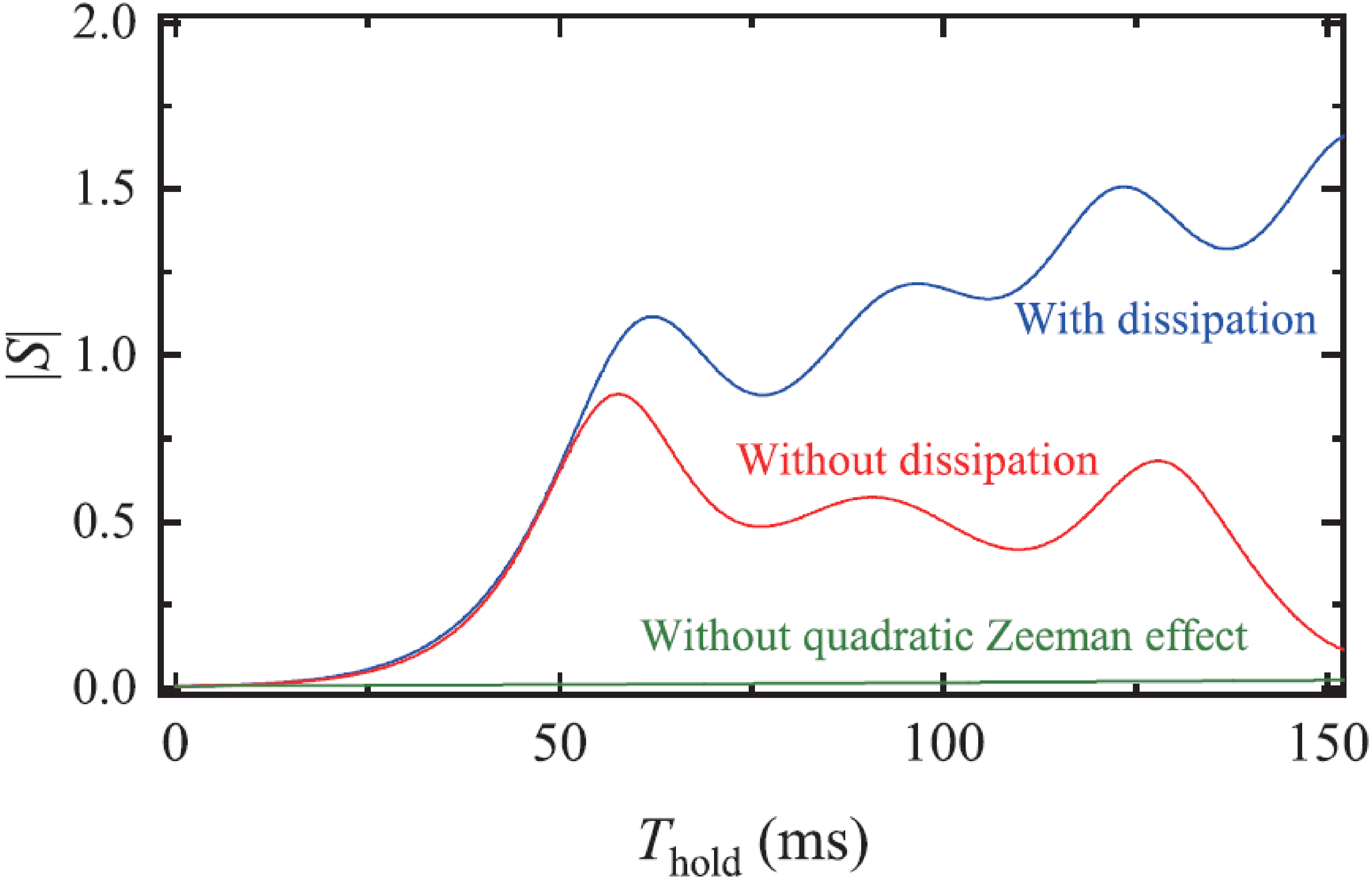


"larmor precession around z-axis"

Coherence formation assisted by spin-dependent particle dissipation



Evolution of the magnetization : numerical simulation



Summary

- **Bose-Einstein condensate of neutral atoms is a meso-scale quantum system with great controllability and an testing ground for studying non-equilibrium quantum dynamics.**
- **Many internal degree of freedom of multi-component BEC will offer a variety of non-equilibrium phenomena.**
- **Spontaneous magnetization in dissipative spinor BEC**
  - **We examined the effect of naturally occurring dissipation by using a Bose-Einstein condensate of spin-2 ^{87}Rb atoms.**
  - **Through experiments and numerical simulations, we show that the spin-dependent particle dissipation gives rise to the coherence formation.**
  - **The result shows that dissipation in nature can contribute to the formation of the quantum coherence.**