Non-Equilibrium Dynamics of a spinor Bose-Einstein Condensate

Department of physics, Gakushuin University

Takuya Hirano
Gakushuin University

- Private University located in Tokyo
- originally established as peer’s school in Kyoto in 1847
- Privatized in 1947
Overview of our group

Members
- Takuya Hirano
- Eto, Yujirō
- Kousuke Shibata
- Ryo Namiki
- Naota Sekiguchi
- Aki Torii

3 graduate students and 4 undergraduates

Topics
- Continuous-Variable (CV) Quantum Key Distribution
- Spinor Bose-Einstein Condensates
- Pulsed CV Entanglement
- Stern-Gerlach method
- F = 2 state
- TOF 15ms

Prof. Eto, Yujiro --> AIST, Japan
Assit. Prof. Ryo Namiki
PostDoctoral Scholar Naota Sekiguchi
Researcher Aki Torii

Assit. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof. Prof.
Continuous-Variable QKD: faint light is detected by homodyne detection

<table>
<thead>
<tr>
<th></th>
<th>Photon counting</th>
<th>particle nature</th>
<th>custom-build for QKD</th>
<th>Require cooling</th>
<th>expensive</th>
<th>sensitive to stray light</th>
</tr>
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<tbody>
<tr>
<td>Homodyne detection</td>
<td>wave nature</td>
<td>commercially available</td>
<td>room-temperature</td>
<td>low cost and small</td>
<td>insensitive to stray light</td>
<td></td>
</tr>
</tbody>
</table>

Advantageous in practical implementation, multiplexing with optical communication

Quantum noise due to uncertainty relation

Limitation on signal discrimination

Multiplexing of CV-QKD with 100 WDM coherent channels

Pulse-resolved measurement of continuous-variable EPR entanglement with shaped local oscillators

\[
\Delta_{B|A}^2 X \Delta_{B|A}^2 P = \left( \frac{\min \Delta^2 (X_B - g_X X_A)}{g_X} \right) \left( \frac{\min \Delta^2 (P_B - g_P P_A)}{g_P} \right)
\]

\[
= \left( \frac{\langle \Delta^2 X_B \rangle - \langle \Delta X_B \Delta X_A \rangle^2}{\langle \Delta^2 X_A \rangle} \right) \left( \frac{\langle \Delta^2 P_B \rangle - \langle \Delta P_B \Delta P_A \rangle^2}{\langle \Delta^2 P_A \rangle} \right)
\]

\[
= 0.82 \pm 0.09 < 1
\]

Ami Shinjo, Yujiro Eto, and TH Optics Express, 27, 17610-17619 (2019).
Why Non-Equilibrium Dynamics in spinor Bose-Einstein Condensates?

Bose-Einstein condensate (BEC) of neutral atoms

meso-scale quantum system with great controllability

testing ground for studying non-equilibrium quantum dynamics

creation of new paradigm of non-equilibrium science
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

\[ F = S + L + I \]

- \( S \): electron spin
- \( L \): electron orbital
- \( I \): nuclear spin

All spin states can be trapped in an optical trap

Novel physics in quantum fluids with many internal degrees of freedom

| \( ^{87}\text{Rb},
\text{ }^{23}\text{Na},
\text{ }^{7}\text{Li},
\text{ }^{41}\text{K} \) | \( F = 1, 2 \) |
| \( ^{85}\text{Rb} \) | \( F = 2, 3 \) |
| \( ^{133}\text{Cs} \) | \( F = 3, 4 \) |
| \( ^{52}\text{Cr} \) | \( F = 3 \) \( (S = 3, I = 0) \) |
| \( ^{4}\text{He}^*,
\text{ }^{40}\text{Ca},
\text{ }^{174}\text{Yb},
\text{ }^{176}\text{Yb} \) | \( F = 0 \) \( (S = 0, I = 0) \) |
\(^{87}\text{Rb BEC with internal degrees of freedom}\)

<table>
<thead>
<tr>
<th></th>
<th>high-field seeker</th>
<th>(m_F)</th>
<th>low-field seeker</th>
</tr>
</thead>
<tbody>
<tr>
<td>(F=2)</td>
<td>-2</td>
<td>0</td>
<td>+1</td>
</tr>
<tr>
<td>(F=1)</td>
<td>+1</td>
<td>0</td>
<td>-1</td>
</tr>
</tbody>
</table>

- 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
  - quantum turbulence, quantum vortex dynamics,
  - phase separation, interface of different components
  - spin dynamics, etc…
Energy level diagram of $^{87}\text{Rb}$ at 20 G

State manipulation

Microwave 6.8GHz + rf 2.0 MHz
2-photon transition

Transmission
0 1

Stern-Gerlach method (SG)

Time evolution and imaging

$F = 1$ and 2

TOF
15ms for $F = 2$

18ms for $F = 1$
Spin dynamics in atomic BEC


Phase separation dynamics of multi-component BECs

Outline

Spin dynamics in atomic BEC


Phase separation dynamics of multi-component BECs


Collisions in Spin-2 spinor BEC

**elastic : spin-exchange collision**

before after

|2, m₁⟩ + |2, m₂⟩ → |2, m₃⟩ + |F, m₄⟩

m₁ + m₂ = m₃ + m₄

ex. |2, 0⟩ + |2, 0⟩ ↔ |2, +1⟩ + |2, −1⟩

coherent evolution between \( m_F \)

**inelastic : hyper-fine changing collision**

before after

|2, m₁⟩ + |2, m₂⟩ → |1, m₃⟩ + |F, m₄⟩

ex.

|2, 0⟩ + |2, 0⟩ → |1, +1⟩ + |2, −1⟩

→ **two-body loss**

Impossible: |2, 2⟩ + |2, 2⟩ → |1, m₃⟩ + |F, m₄⟩

\( m_F \) dependent loss


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

Experimental techniques

Magnetic shield

BEC machine in a magnetic shield room

March 2010
Experimental procedure

- Before microwave irradiation
  - Pure initial state

- Experimental parameters:
  - Bias mag. field: 200 mG
  - Microwave frequencies:
    - ①: 6.834264565 GHz
    - ③: 6.834542658 GHz
  - Resonant light:
    - ②: 780.24 nm

High fidelity initial-state preparation

Before microwave irradiation

③ without resonant light

③ with resonant light

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

**Mixed initial state (w/o light)**

- Ratio of $m_F=0$ is 0.9 @0ms
- Rapid decrease even @10ms

**Pure initial state (with light)**

- Almost pure $m_F=0$
- Remains in $m_F=0$ up to 30ms

$m_F=0$ is a quasi-stable state
Spin rotation by rf pulse

If magnetic field is sufficiently low, Zeeman shift is linear.

Spin state rotation
resonant rf pulse

Quantization axis along bias magnetic field

After rf pulse

$B_z$
spin rotation by rf pulse

Application of two $\pi/2$ pulses

- Application of two $\pi/2$ pulses
- spin rotation by rf pulse
- $\sin(\omega t + \phi)$
- $\sin(\omega t)$

$m_F = -2$

$m_F = 0$
Application of $\pi/2$ pulse before Stern-Gerlach separation

Spin states are rotated by 90 degree.

We can effectively rotate the measurement axis.
Experimental procedures

Trap frequency
axial: 64Hz
radial: 180Hz

Bias magnetic field
$B_z = 200 \text{mG}$

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

② Preparation of $F=2$, $m_F=0$ BEC

③ $m_F$ population measurement

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

(a) Without rf

$T_{\text{hold}}$

Measurement axis is parallel to bias

(b) With rf

$T_{\text{hold}}$

$\pi/2$

Measurement axis is perpendicular to bias
Evolution of $m_F=0$ state: measurement axis parallel to mag. field

- Mixed initial state (w/o light)
  - $\triangle: m_F=\pm2$
  - $\square: m_F=\pm1$
  - $\bullet: m_F=0$

- Pure initial state (with light)
  - $\triangle: m_F=\pm2$
  - $\square: m_F=\pm1$
  - $\bullet: m_F=0$

- 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

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

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

Results were different for each measurement under same experimental condition.
Evolution of $m_F=0$ state: meas. axis perpendicular to mag. field

Spin state before $\pi/2$ irradiation

$|0\rangle_z = m_F = 0$

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

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

Random values in a range $+2$~$-2$
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)

Note that the magnetic ground state of \( F=2 \) \(^{87}\text{Rb} \) BEC is cyclic or polar.
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
   $\rightarrow$ 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"
Control of BEC spins by Ramsey Interferometer

Initial state

RF

Spin precession

RF

Time

$\pi/2$

$m_F = +2$

$+1$

$0$

$-1$

$-2$

B

B

B
Spin dynamics in atomic BEC


Phase separation dynamics of multi-component BECs


Case a: Ramsey Interferometer

\[ \langle S_z \rangle = \sum_{m_F=-2}^{2} m_F P_{m_F} \]
Case a: characteristic density profile

For short $T$ (130 $\mu$s):

For long $T$ (13 ms):

(a) [Graph showing density profile]

(b) [Graph showing density profile]
Effect of magnetic-field gradient
Effect of magnetic-field gradient

Without gradient field

With gradient field
Effect of magnetic-field gradient

Position dependence of precession frequency
⇒ helical spin-configuration

Without gradient field

With gradient field

Position-dependent spin direction

Higbie et al. reported shorter decay time for larger gradient field in thermal atomic cloud: PRL 95, 050401 (2005).
Case b: Spin echo method

Removal of the effects of
- Magnetic-field gradient
- Slow field fluctuations
⇒ long coherence time of $<S_z>$
Prolonged coherence of $\langle S_z \rangle$ (T=1ms)

Case a: Ramsey ($\pi/2 + \pi/2$)

Case b: Spin echo ($\pi/2 + \pi + \pi/2$)
AC Magnetometer

\[
\langle S_z \rangle \propto \sin 2\theta = \sin \{ g_F \mu_B \hbar [\int_0^{\frac{\tau}{2}} B_{AC}(t) dt - \int_{\frac{\tau}{2}}^{\tau} B_{AC}(t) dt] \} 
\]
Magnetometer using spinor Bose-Einstein condensates

<table>
<thead>
<tr>
<th>method</th>
<th>Phase contrast imaging</th>
<th>Spin-echo</th>
</tr>
</thead>
<tbody>
<tr>
<td>resolution</td>
<td>8.3 pT/√Hz @120µm²</td>
<td>12 pT/√Hz @100µm²</td>
</tr>
<tr>
<td>response</td>
<td>dc</td>
<td>ac</td>
</tr>
<tr>
<td>response tunability</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>tolerance to slow field variation</td>
<td>no if duty ratio is low</td>
<td>yes</td>
</tr>
</tbody>
</table>
Detection of stray ac field by BEC

Fitting function
(assume 50Hz ac field by supply line)

\[
\langle S_z \rangle = 2 \sin \left\{ g_F \mu_B \hbar \left[ \int_0^{\tau/2} B_{AC}(t) dt - \int_{\tau/2}^{\tau} B_{AC}(t) dt \right]\right\}
\]

\[
B_{AC}(t) = B_{50} \sin \{2\pi \times (50t + \varphi_{50})\}
\]

\[
B_{50} = 9.5 \text{ nT, } \varphi_{50} = -0.5
\]

If the fitting is correct, application of an opposite phase 50 Hz magnetic field should suppress stray ac magnetic field.
Reduction of stray ac field

Application of an opposite phase 50 Hz magnetic field

- With 50Hz opposite phase field
  \[ B_{50} = 9.5 \text{ nT}, \varphi_{50} = -0.5 \]

- With 50Hz+100Hz field
  \[ B_{50} = 9.5 \text{ nT}, \varphi_{50} = -0.5 \]
  \[ B_{100} = 3.5 \text{ nT}, \varphi_{100} = 1.5 \]

Magnetic field noise synchronous with power supply is suppressed \( \leq 1 \text{ nT} \)
Visibility of spin precession for longer time

Visibility decays in several tens of milliseconds in the presence of a magnetic field gradient.
Center of mass movement by field gradient

Center of mass of each $m_F$ components moves under field gradient
Population of each mF component and atom loss

- $m_F=0$
- average of $m_F=+1$ and $-1$
- average of $m_F=+2$ and $-2$

Spin-state dependent movement due to magnetic field gradient
- $\rightarrow$ population change by spin-exchange collision
- $\rightarrow$ atom loss by inelastic collision
Control by periodic application of $\pi$ pulses

The force by field gradient depends on spin states.
$\Rightarrow$ $\pi$ pulse inverts the sign of $m_F$, the force also inverts.
$\Rightarrow$ periodic application of $\pi$ pulses

Application of $\pi$ pulses
Control by periodic application of $\pi$ pulses

The force by field gradient depends on spin states.
⇒ $\pi$ pulse inverts the sign of $m_F$, the force also inverts.
⇒ periodic application of $\pi$ pulses
Time dependence of population and atom number

Population of each $m_F$ component

- $m_F=0$
- average of $m_F=+1$ and $-1$
- average of $m_F=+2$ and $-2$

Application of $\pi$ pulses

Suppression of Spin exchange and inelastic collisions
Consecutive in situ Imaging of a Bose-Einstein Condensate for a Precise Spatial Magnetometry

N. Sekiguchi, A. Torii, R. Kuramoto, D. Fukuda, K. Shibata, and T. Hirano
Department of Physics, Gakushuin University, Tokyo, Japan

Motivation

State-of-the-art magnetometers

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Sensitivity (nT/Hz^{1/2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>FMM</td>
<td>10^{-10}</td>
</tr>
<tr>
<td>Hall probe</td>
<td>10^{-11}</td>
</tr>
<tr>
<td>NV probe</td>
<td>10^{-12}</td>
</tr>
<tr>
<td>PND</td>
<td>10^{-13}</td>
</tr>
<tr>
<td>BCC</td>
<td>10^{-14}</td>
</tr>
<tr>
<td>MCF</td>
<td>10^{-15}</td>
</tr>
<tr>
<td>SQUID</td>
<td>10^{-16}</td>
</tr>
<tr>
<td>GMR</td>
<td>10^{-17}</td>
</tr>
<tr>
<td>VSM</td>
<td>10^{-18}</td>
</tr>
<tr>
<td>EPS</td>
<td>10^{-19}</td>
</tr>
<tr>
<td>Hysus</td>
<td>10^{-20}</td>
</tr>
</tbody>
</table>

Spinor BEC for magnetometry

- Long coherence time
- Negligible thermal diffusion
- Density-independence of Larmor precession

Consecutive imaging for spatial magnetometry (this work)

- $^{87}$Rb BEC of F = 2
- Phase contrast imaging + Faraday rotation measurement

- Spin dynamics of $^{87}$Rb BEC in an optical trap were observed.
- Tensor atom-light interaction was indicated.
- Phase of a Larmor precession of the BEC was able to be determined within sensitivity of 0.04 rad.
- A corresponding single-shot sensitivity to a magnetic field was ~ 5 nT.

Experimental setup

Dual port Faraday imaging + Phase contrast imaging

Example of the consecutive imaging

\[
\delta = 606 \text{ MHz, } \theta = 57^\circ, I_p = 5.1 \text{ mW/mm}^2
\]

Take mean values over the frames.
Spin dynamics in atomic BEC


Phase separation dynamics of multi-component BECs


Observation of dipole-induced spin texture


Dipolar interactions
long-range and anisotropic
→ Novel non-equilibrium behaviors

Larmor averaged effective magnetic field

\[ b_{\text{eff}} = \frac{\mu_0 g \mu_B}{8\pi} \int dr' \frac{1 - 3e^2}{|r - r'|^3} \left[ 3f_z(r')\hat{z} - f(r') \right] \]

In a helical spin configuration, direction of the effective magnetic field is different from that of the spin vector, spin precession occurs and a spin pattern is expected to be formed.
Observation of dipole-induced spin texture

The double peaks are generated along the z direction in $m_F \neq 0$ components as $T_{\text{hold}}$ is increased.
Observation of dipole-induced spin texture

MDDI: magnetic dipole-dipole interaction

Larmor precession around the effective magnetic field gives spin $\pm z$ component.

There appears two regions of $F_z > 0$ and $F_z < 0$.

These features can not be numerically simulated without MDDI.
Spin dynamics in atomic BEC

Phase separation dynamics of multi-component BECs
Phase separation and domain formation

**Phase-separation condition**

\[ a_{12}^2 > a_{11} a_{22} \]

When two spatially overlapping immiscible BECs are prepared, domain structures are spontaneously formed.

H.-J. Miesner et al., PRL 82, 2228 (1999)
Phase-separation near Feshbach resonance

$B_{ev}$

**Experiment**

(2,-1)

(1,+1)

**Theory**

(2,-1)

(1,+1)

$K_{12}$

$\Delta a$

0.5  
1  

0  
0.5

Spin dynamics in atomic BEC

Phase separation dynamics of multi-component BECs
Suppression of relative flow by multiple domains in two-component Bose-Einstein condensates


In equilibrium

Phase-separation condition \[ a_{12}^2 > a_{11}a_{22} \]

BECs
Mixture of binary BECs

Time evolution

miscible

immiscible?

When two spatially overlapping immiscible BECs are prepared, domain structures are spontaneously formed.

H.-J. Miesner et al., PRL 82, 2228 (1999)

Under non-equilibrium condition?

We generate the relative flow between the two-component BECs by a spin-dependent potential gradient.

Observation of quantum tunneling was reported.
Experimental procedure

Prepare BEC in an optical trap

Creation of Two-component BEC by application of resonant rf pulse

mag. field after 0 ms (no domain structure)

mag. field after 40 ms (after domains formation)

We investigate influences of domain structures on the fluidity of immiscible two-component BECs and, conversely, influences of non-equilibrium fluid flow on the domain structures.
Multiple domain structures are formed after 40 msec.

Experiment

\[ T_{\text{hold}} = \begin{array}{cccc}
0\text{ms} & 20\text{ms} & 40\text{ms} & 60\text{ms} & 80\text{ms} \\
m_F = -2 & & & & \\
m_F = -1 & & & & \\
\end{array} \]

Simulation

\[ m_F = -2 \]

\[ m_F = -1 \]

Spontaneous spin domain formation

\( dB_z/dz \sim 0 \text{ mG/cm} \)
Relative center of mass motion

\( (dB_z/dz \sim 15 \text{ mG/cm}) \)

Application of gradient field without domains

- \( m_F \) dependent gradient force
- immiscible
Center of mass motion
\((dB_z/dz \sim 15\text{mG/cm})\)

With domain structures

Suppression of relative motion
Center of mass position after 10 msec
(dependence on magnitude of $dB_z/dz$)
When the gradient field is applied immediately after preparation of binary BEC

Experiment

Simulation

Two-component BECs separate each other without forming domain structures.
When the gradient field is applied from 40 msec:

after formation of domain structures

Experiment

Simulation

Even for a large gradient about 500 mG/cm, the two-component BECs move while maintaining a multiple domain structure.
Outline

Spin dynamics in atomic BEC

Phase separation dynamics of multi-component BECs

Collision-induced dynamics in Multi-Component Bose-Einstein Condensates


How the miscibility of two-component BECs influences the collision dynamics?

Bounce? or Mutually penetrate?
Collision-induced dynamics in Multi-Component Bose-Einstein Condensates


Miscibility of $^{87}$Rb BEC

$\Delta = a_{ij} - \sqrt{a_{ii}a_{jj}} < 0$  \hspace{1cm} \Delta > 0$

or

Two-component BECs

<table>
<thead>
<tr>
<th>State</th>
<th>$a_{11}$</th>
<th>$a_{22}$</th>
<th>$a_{12}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>2, -2\rangle,</td>
<td>1, -1\rangle$</td>
<td>$98.98a_B$</td>
</tr>
<tr>
<td>$</td>
<td>1, 0\rangle,</td>
<td>1, -1\rangle$</td>
<td>$100.86a_B$</td>
</tr>
<tr>
<td>$</td>
<td>1, 1\rangle,</td>
<td>1, -1\rangle$</td>
<td>$100.40a_B$</td>
</tr>
</tbody>
</table>
Collision-induced dynamics in Multi-Component Bose-Einstein Condensates


Miscibility of $^{87}$Rb BEC

$\Delta = a_{ij} - \sqrt{a_{ii}a_{jj}} < 0$miscible

or

$\Delta > 0$immiscible

$|2, -2\rangle, |1, -1\rangle$ $\Delta = -0.70a_B$miscible

$|1, 0\rangle, |1, -1\rangle$ $\Delta = 0.46a_B$weakly

$|1, 1\rangle, |1, -1\rangle$ $\Delta = 0.92a_B$strongly immiscible
Collision-induced dynamics in Multi-Component Bose-Einstein Condensates: Poster PA204
Collision-induced dynamics in Multi-Component Bose-Einstein Condensates

Relative center-of-mass position

Bounce between miscible pairs

penetration between immiscible pairs

numerical simulation
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.

Spin dynamics
- Spontaneous magnetization in Dissipative Spinor BEC
- AC magnetometer and reduction of magnetic fields noise
- Observation of dipole-induced spin texture

Phase separating dynamics
- Suppression of relative flow by multiple domains in two-component BEC
- Collision-induced dynamics in miscible and immiscible two-component BECs