Experimental study of atomic Bose-Einstein condensates with internal degrees of freedom

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Topics
• BEC of Rb atoms
• Contineous-variable (CV) quantum information using pulsed light
  Quantum cryptography using pulsed homodyne detection
  “Plug & play” and free-space implementation at telecommunication. wavelength
• CV quantum entanglement with pulsed light
• Pulsed squeezing at telecomm. wavelength
1. Motivation

2. Experimental apparatus

3. Atomic BEC with internal degrees of freedom
   - Dynamical Properties of $^{87}\text{Rb}$ Spin-2 BEC
   - Optical Confinement of Binary BEC: simultaneous trap of F=1 and F=2
   - Vortex Formation via magnetic field reversal

Thanks to former members: T. Kuwamoto, H. Usuda, K. Hamazaki, Y. Nara

4. Summary
Motivations

Spin degrees of freedom $F=2$ spinor condensate

- Is ground state of $^{87}\text{Rb}$ ferro, anti-ferro, or cyclic states?
- Mixture of $F=1$ & $F=2$ spinor BEC
- Vortex states in spinor BEC
- etc…

Novel Physics in Quantum Fluids with spin Degree of Freedom
Experimental setup (1)

Double-MOT

- push beam

1st MOT
- 20 l/s ion pump
- 150 l/s ion & Ti:sublimation pump
- ultra-cold $^{87}$Rb < $10^9$

2nd MOT
- glass cell

- ECLD (handmade)
- TC-40 tapered amplifier laser
- LD (injection locked)

- frequency stabilization
- repump

55mW
- to 1st MOT
- to 2nd MOT

2mW
- 55mW
- 280mW
- probe
- pump (MOT to MT)
- push (1st to 2nd MOT)
Atoms in an optical trap

Optical trap potential

\[ U = -\frac{1}{2} \alpha \cdot |E|^2 \]
\[ \propto -\frac{P}{\Delta} \]

\( \alpha \): polarizability, \( E \): electric field
\( P \): laser power
\( \Delta \): detuning (f_{laser} - f_{resonance})

Spin degrees of freedom are liberated in an optical trap.

First success in Jan. 2000
Setup of Optical Trap

Top view

- OT Beam (axial)
- OT Beam (radial)
- Coils for magnetic trap
- Mirror
- 5 deg.
- r (radial)
- g
- z (axial)
- \( \lambda : 850 \text{ nm} \)
- Power fluctuation <1%
- Beam waist radius
  - radial: 90 \( \mu \text{m} \)
  - axial: 24 \( \mu \text{m} \)
- Potential depth of OT
  - \( U \sim 1.0 \ \mu \text{K} \)

- Create BEC in magnetic trap
- Overlapping Trapping beam
- 120ms
- Adiabatic increase in power
Lifetime of BEC in Optical Trap - Stretched State ($F=2$, $m_F=-2$) -

- Loss rate
  (in the region of $N < 1 \times 10^5$)
  
  \[ \tau_{\text{magnetic trap}} \sim 7 \text{ s} \]
  \[ \tau_{\text{optical trap}} \sim 4 \text{ s} \]
  
  photon scattering rate
  \[ 2 \times 10^{-3} \text{ /s} \]

Number of condensed atoms vs. Trap time (s)

Absorption image of the BEC in the optical trap
Manipulation of Spin States

energy level diagram of $^{87}$Rb ground hyperfine states

B=20G

$m_F$

2

1

0

-1

-2

Initial state

F = 2 state

14.020 MHz

$\Delta = 58$ kHz

14.078 MHz

BEC

optical trap

homogeneous magnetic field

B=20G

rf field

(Frequency is swept)

Parameter of rf field

center frequency : 14.078 MHz

sweep range : 80 kHz

sweep time : 1～3 ms

It is possible to selectively prepare any states.
Spatial separation by Stern-Gerlach method

We could prepare highly polarized (almost pure) $m_F=0$ BEC. Transfer rate $>90\%$
Decay of $F=2$, $m_F=0$ BEC in OT at $B = 1.5G$

Atoms in BEC initially polarized in $F=2$, $m_F=0$ state.

$m_F=\pm 1$ components appeared during decay process.

Time evolution of $m_F = -1, 0, +1$ components.

Total-spin-conserved spin-relaxation process.
Magnetic field dependence of spin-mixing dynamics

Oscillation in spin populations
@ $B = 0.75 \text{G}$, $0.3 \text{G}$

cf. F=1 Josephson Oscillation:
Nature Physics 1, 111 (2005)
If the $F = 2 \ ^{87}\text{Rb}$ 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)]
Magnetism of F=2 $^{87}$Rb BEC

If cyclic

initial config.  
$m_F = -2 & +2$

$m_F = -2 & 0 & +2$

actually...

$m_F = -2 & +2$

indicates anti-ferromagnetic, but small population in $m_F = \pm 1$...
Simultaneous trap of $F=1$ and $F=2$ Rb BEC

JILA : magnetic trap
capable of trapping only weak field seeking states

Our experiment : optical trap
capable of trapping any states, even for anti-parallel magnetic moment
Control of magnetic field
Microwave transition

\[ \Delta \nu \approx 535 \text{[kHz]} \]

\[ B \approx 255 \text{[mG]} \]

5S_{1/2} \rightarrow F=1, g_F=-1/2

\( F=2, g_F=1/2 \)
Experimental setup

Microwave: 6.83415GHz, ~15dBm

Optical trap:
- 850nm
- \( \nu_r \approx 237 \text{ Hz} \)
- \( \nu_z \approx 21 \text{ Hz} \)

Wave guide
- Helmholtz coil
- Trap beam

Amplifier
- Solid state switch
- Isolator

Microwave synthesizer: ~6.8GHz
Time evolution for $N_{F=1} = N_{F=2}$ (without Stern-Gerlach)

**Trap time**
- 0 ms
- 200 ms
- 400 ms
- 600 ms

**TOF**
- 22 ms

**Field gradient** $\frac{\partial B}{\partial z} \sim -30 \text{ mG/cm}$

**Change bias field**
- $\Delta B \sim 0.3 \text{ mG}$
- $\Delta E \sim 20 \text{ nK}$

**Force directions are reversed.**
Center of mass movement of F=2 component

Change bias field
Experiment procedure

|2,-2> → |1,-1> Microwave transition

Initial state

Change bias field

Time (ms)

Optical trap

Magnetic trap

Bias field

Micro wave

Probe light

Evolution time 22
Topological Vortex Nucleation in Bose-Einstein Condensates

\[ \mathbf{B} \times (t) \mathbf{B} \perp (r) \mathbf{B} \]

500mG

\[ B_{total} \cong B_z \]

Invert B

\[ (B_z) = 0, B_{total} \cong \mathbf{B}' \]

87Rb : F=2, \( m_F = 2 \)

\[ \oint_c \mathbf{V} \cdot d\mathbf{s} = \frac{\hbar}{m} \cdot 8\pi = \frac{\hbar}{m} \cdot 2\pi \cdot 4 \]


23Na (F=1, \( m_F = -1 \))
87Rb (F=2, \( m_F = 2 \))
Kyoto group, Annual meeting JPS, 2004, 27aXG-3

Atomic spin

\[ ^{87}\text{Rb} : F=2, m_F = 2 \]

\[ ^{23}\text{Na} (F=1, m_F = -1) \]

\[ ^{87}\text{Rb} (F=2, m_F = 2) \]
Observation of vortex

Experimental procedure
1. Create BEC in a magnetic trap
2. Invert the magnetic field
3. Absorption imaging
Simultaneous imaging from two directions

Inverting time: 3~13ms

- No trapping potential along z axis after inverting the bias field
- We can observe vortex up to 10ms trap-time

TOF: 19ms, Inverting time: 5ms
Summary

• Ground state of $^{87}$Rb Spin-2 BEC
  
  For $m_F=0$ initial state, decay at various magnetic field strengths
  → Spin relaxation, population oscillation
  
  For $m_F=\pm 2$ initial state, atoms remain in $m_F=\pm 2$
  → Antiferromagnetic

• Optical Confinement of Binary BEC: $F=1$ and $F=2$
  
  Spatial separation, center of mass movement, domain structure were observed.

• Vortex Formation via magnetic field reversal
  
  Charge 4 vortex, simultaneous imaging from two directions
  up to 10 msec in magnetic trap,
  up to ~20 msec in optical trap.