QIBEC
Quantum Interferometry with Bose Einstein Condensates

CNR-INO Experimental Unit

Kickoff meeting, 2-3 February 2012, Firenze
Trapped Mach Zender Interferometry with BEC

Operation
- Sensitive to the difference in potential energy between the two wells
- Read-out phase $\phi \sim \Delta ET/h$
- Sensitive to gravity, accelerations, electromagnetic field gradient, etc…

Main goals within the QIBEC project
- Operation of the interferometer with high sensitivity
- Exploitation of entanglement towards Heisenberg limited resolution

Target breakthrough
A new type of sensor with both high spatial resolution and high sensitivity
Trapped Mach Zender with BEC: main obstacles

- Interaction induced decoherence
- Heating and finite temperature
- Decoherence induced by the trapping potential or other external fields
- Losses
- Atom number counting with single atom resolution
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Interaction induced decoherence

\[ |\Psi\rangle = \sum_{n=-N/2}^{N/2} c_n \left[ \frac{N}{2} + n, \frac{N}{2} - n \right] \]

\[ E_i(n) = U_C \left[ (\frac{N}{2} + n)^2 + (\frac{N}{2} - n)^2 \right] + U_D \left[ (\frac{N}{2} + n)(\frac{N}{2} - n) \right] \]


If \( U_C = U_D / 2 \)

\[ E_i(n) = U_C \left[ (\frac{N}{2} + n + \frac{N}{2} - n)^2 \right] = U_C N^2 \]
A weakly interacting condensate with a K isotope

$^{41}\text{K}$ boson, condensed

$^{40}\text{K}$ fermion

$^{39}\text{K}$ boson, $a = -33a_0$


De Sarlo et al, PRA 75, 022715 (2007)

Atoms in $m_F=1$

$a(B) = a_{bg} \left( 1 - \frac{\Delta}{B - B_0} \right)$

$a(B) \approx \frac{a_{bg}}{\Delta} (B - B_{ZC}) \rightarrow \frac{\Delta a}{\Delta B} = 0.6 \ a_0 / G$

Very high degree of tunability !!

Atom interferometry on the zero crossing of the broad Feshbach resonance
A weakly interacting condensate with a K isotope

Magnetic dipolar interaction

Quantum enhanced sensitivity

Spatial Mach Zender Interferometer

Uncorrelated particles

Quantum entangled particles

\[ \Delta \phi \sim \frac{1}{\sqrt{N}} \] (Shot noise limit)

\[ \Delta \phi \sim \frac{1}{N} \] (Heisenberg limit)

Test of linear vs non linear interferometer for different values of the scattering length


Some numbers

Coherence time for a residual interaction

\[ t_c = \frac{1}{\sqrt{N}} \frac{h}{U_c} \]

for \( a_S < 10^{-3} a_o \), \( N=10000 \), \( \omega_{\text{avg}}=65 \text{ Hz} \) \( \rightarrow \) \( t_c \sim 10000 \text{ s} \)

Single mode hypothesis fulfilled \( \rightarrow \) \( E_{\text{int}}/E_K < 10^{-1} \) for \( a_{\text{dipolar}} \sim 0.3 a_o \)
Trapped Mach Zender with BEC: main obstacles

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Heating and finite temperature

Two mode operation requires low temperature and low heating during the whole sequence

Ground state occupation, $|C_0|^2 = 1 \rightarrow k_B T < h\omega$, for $T=3\, \text{nK}$, for $65\, \text{Hz}$

For $\lambda = 1064\, \text{nm}$, $E_{\text{rec}} \sim 200\, \text{nK}$!!

Fast splitting without excitations for the creation of strongly squeezed state and for beam splitter operation

Input from ULM, TU-WIEN and UHEI on application of OC theories (manipulation of the potential barrier and scattering length)
Trapped Mach Zender with BEC: main obstacles

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Decoherence induced by the trapping potential

\[ \Delta \phi \sim 1/N \sim 1 \text{ mrad (for } N=1000 \text{ atoms)} \]

Uncontrolled energy shifts < 1 mHz (for 1 sec operation)

Using two independent dipole traps for the two wells

- \( E_{L,R} \sim 10 \text{ kHz} \rightarrow 10^{-7} \text{ power stability !!!} \)
- \( \Delta E_g \sim 1 \text{ kHz for } d \sim 1 \mu m \rightarrow 1 \text{ pm pointing stability !!!} \)

Way out:
- common mode trapping power fluctuations
- use of lattices to control the distance \( d \)
Decoherence induced by the trapping potential

- Super-Lattice

\[ \lambda_1 = 1064 \text{ nm} \]

Radial confinement

\[ \lambda_2 = \lambda_1 / 2 = 532 \text{ nm} \]

\[ d = \lambda_1 / [2 \sin(\theta / 2)] \approx 10 \mu\text{m} \]


- Use of a lattice leads to common mode rejection of light shifts in the two wells

- An array of interferometers allows rejection of uncontrolled spurious forces (vibrations, magnetic field gradients, etc…)

CNR-Th: Differential phase estimation protocol

- Increase of the sensitivity, full exploitation of the atom number (not possible in a single interferometer). \[ \sqrt{M} \] increase of the sensitivity with \( M \) the number of interferometers.
Trapped Mach Zender with BEC: main obstacles

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Losses

M. Zaccanti et al., Nature Physics 5, 586 (2009)

Effect of three body losses on the preparation of entangle states
Y. Li, Y. Castin and A. Sinatra, PRL 100, 210401 (2008)

Three body losses rate on the zero crossing $< 1 \text{ mHz}$ for $N \sim 1000$

T $\sim 1 \text{ s}$

$\nu_{\text{trap}} \sim 100 \text{ Hz}$

Other losses and decoherence sources: background losses and trapping light scattering

CNRS-Th
UHEI

Heisenberg limit
Trapped Mach Zender with BEC: main obstacles

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Input from the other units


Possible route

• Fluorescence imaging of N atoms

• $N_{ph}$ scattered by every atom and only $\beta N_{ph}$ detected with $\beta \sim 0.1$

• Single atom resolution requires $\sqrt{N\beta N_{ph}} < \beta N_{ph} \rightarrow \sqrt{N} < \sqrt{\beta N_{ph}} \rightarrow \frac{N}{\beta} < N_{ph}$

• Distinguish between different atoms to keep $N$ and $N_{ph}$ low (beware of background noise)

• Trap and cool the atoms preventing radiative losses

• 3D lattice using Sub Doppler cooling now possible with K

400 atoms with 99.5% efficiency

Experimental apparatus

2D Mot

3D Mot

Science chamber
Experimental sequence

• 2D MOT: $2 \times 10^{10}$ atoms/s with a low average velocity of 25 m/s

• 3D MOT: $3 \times 10^{10}$ atoms in 5 seconds

• C-MOT and Molasses
  \[ N \sim 2 \times 10^{10}, \ T \sim 25 \ \mu K, \ n \sim 10^{11} \text{cm}^{-3}, \ \rho \sim 10^{-5} \]

  Efficient Sub Doppler cooling

M. Landini, et al. PRA (2011)
Sub Doppler cooling
Sub Doppler cooling

$^{41}\text{K}$

$^{39}\text{K}$
 Experimental sequence

- Magnetic transport to the science chamber with a movable magnetic field gradient and with atoms in the F=1, m_F=-1

- Ramping up of a tightly focused laser (30 W, 25 μm waist, 1064 nm) and switching off of the magnetic field gradient abruptly after 2 sec
  
  \[ N \sim 10^7, \quad T \sim 220 \, \mu K, \quad n \sim 5 \times 10^{13} \, \text{cm}^{-3}, \quad \rho \sim 10^{-4} \]

- Single beam evaporation at 40 G with 75 a_o

- Additional evaporation with a vertical dimple

- BECs with \(10^5\) atoms in 20 sec
Experimental sequence

F=2

F=1

$\nu$ (MHz)

$B$ (G)

$F=1$

F=1

$F=1$

$m_f=\pm 2$
$m_f=\pm 1$
$m_f=0$
$m_f=\pm 1$

a ($a_0$)

B (G)
Double well potential laser system

Double well potential

Beatnote detection for phase and frequency locking at arbitrary frequency difference

Mephisto MOPA 36 W @ 1064 nm

SHG Unit 3W @ 532 nm

Mephisto 200 mW

+ Nufern Amplifier 10 W

Photonic Crystal Fibre
Possible sinergies

TU-WIEN

• Fast creation of squeezing and operation of the interferometer with non null scattering length
• Single atom resolution

UHEI

• Creation of squeezed states
• Single atom resolution
• Large spacing optical lattices

CNRS

• Effect of losses on the entanglement formation
• Finite temperature effect

ULM

• Optimal control theory applied to our double well trap
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