Atomic Quantum Sensors Based on Cold Atoms

Wolfgang Ertmer

Gottfried Wilhelm Leibniz Universität Hannover

Institute for Quantum Optics (IQ)
Centre for Quantum Engineering and Space-Time Research (QUEST)
Laser Centre Hannover (LZH)
Quantum engineering
Degenerate Quantum Gases
Quantum Techniques
Atomic Inertial Sensor

REVIEW OF QUANTUM PHYSICAL ACHIEVEMENTS
Quantum Engineering

- Non-classical light and matter wave fields or modes
- Quantum non-demolition measurements
- Squeezing, down to low frequencies
- Light & matter wave interferometry “beyond classical limits”
- Entanglement & quantum correlation of light fields, atoms, molecules, ions, and macroscopic bodies
- Laser cooling and trapping of atoms, molecules, ions, and macroscopic bodies to ultra-low temperatures
Degenerate Quantum Gases

- **Bose Einstein Condensates (BEC)**
  - *Coldest matter in the universe*
- Degenerate ultra-cold *Fermi* gases
  - “Collision-less”
- Degenerate *mixtures*, spinor gases
- Atom lasers
  - *Brilliant matter wave sources*
- Atom chips
  - *Integrated atom optics*
Quantum Techniques

- Quantum information
  - Quantum cryptography, teleportation, computing
- Quantum metrology
- Non-classical light and matter wave sources
- (Light and) Matter wave interferometry
  - Interferometry at the quantum limit and beyond
    - Gravitational wave detection
    - Atomic clocks
    - Inertial sensing
Overview (Part I)

- Motivation
- Introduction to coherent manipulation of matter waves
- Realization of an atom interferometer with cold atoms
  - $\pi/2 - \pi - \pi/2$ pulse atom interferometer
  - Cold atom Sagnac interferometer
  - Gyroscopes, gravimeter, gradio-gravimeter

Part II: Exploring the Potential of Ultra Cold Gases for Fundamental Tests in Space
Atomic Sensors
-an alternative technique
Alternative Gravimeter → Atomic Inertial Sensor

Accuracy of $\frac{\Delta g}{g}$:

1 part in $10^9$

1 Gal = $10^{-2}$ m/s$^2$
## Gravity sensing

<table>
<thead>
<tr>
<th>Type</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geographical gravity variations</td>
<td></td>
</tr>
<tr>
<td>• global scale</td>
<td>( \sim 10^{-3} ) g</td>
</tr>
<tr>
<td>• regional scale</td>
<td>( \sim 10^{-5} ) g</td>
</tr>
<tr>
<td>Free air gravity gradient</td>
<td>( \sim 3 \times 10^{-7} ) g/m</td>
</tr>
<tr>
<td>Tidal effects</td>
<td></td>
</tr>
<tr>
<td>• basic tides</td>
<td>( \sim 10^{-7} ) g</td>
</tr>
<tr>
<td>• elastic response</td>
<td>( \sim 10^{-8} ) g</td>
</tr>
<tr>
<td>• ocean loading</td>
<td>( \sim 10^{-8} ) g</td>
</tr>
<tr>
<td>• polar motion</td>
<td>( \sim 10^{-9} ) g</td>
</tr>
<tr>
<td>Environmental effects</td>
<td></td>
</tr>
<tr>
<td>• atmospheric pressure</td>
<td>( \sim 3 \times 10^{-10} ) g/mbar</td>
</tr>
<tr>
<td>• water table</td>
<td></td>
</tr>
<tr>
<td>Man-made environmental changes</td>
<td></td>
</tr>
<tr>
<td>• trains, trucks, elevators, people, ...</td>
<td>( \sim 10^{-9} ) g</td>
</tr>
<tr>
<td>• major construction work</td>
<td>( \sim 10^{-8} ) g</td>
</tr>
<tr>
<td>Geological and geophysical effects</td>
<td></td>
</tr>
<tr>
<td>• postglacial rebound</td>
<td>( \sim 10^{-9} ) g/year</td>
</tr>
<tr>
<td>• tectonic plate movements</td>
<td>( \sim 10^{-9} ) g/year</td>
</tr>
<tr>
<td>• change in ocean levels</td>
<td></td>
</tr>
<tr>
<td>• core/mantle boundary effects</td>
<td></td>
</tr>
<tr>
<td>• inner/outer core boundary effects</td>
<td>( \sim 10^{-12} ) g</td>
</tr>
</tbody>
</table>

Rotation sensing

**multidisciplinary applications:**
astronomy, satellite navigation, geology, geodesy

\[ \Omega_E \approx 7.2 \times 10^{-5} \text{ rad/s} \]

Effects:

- seismology
- tidal forces
- variation of the earth’s rotation
- relativistic effects

Resolution:

\[ 10^{-9} \text{ rad in 1 year} \]
Interest in an \textit{(atomic) inertial sensor}?

„best-possible experimental realisation of the free fall„

• purely gravitational coupling
• non-magnetic and neutral,
  no geometry dependence,
  no ionisation, no aging
  (patch effects)

need for femto-g precision
Fields of Interest for Atomic Inertial Sensors:

• inertial standards/references
• earth observation
• measurement of relativistic effects & gravity
• pioneer anomaly
• testing the weak equivalence principle
• drag-free sensors perhaps in gravitational wave detectors?
Beam splitters and mirrors for Atoms

INTRODUCTION TO COHERENT MANIPULATION OF MATTER WAVES
Atom interferometry

Is the key to use 1000.000.000 atoms as inertialsensor?
Wave nature of matter

classical properties

quantum features

\[ m_{at} \cdot \vec{v}_{at} = \vec{p}_{at} = \hbar \cdot \vec{k}_{at} \]

\[ m_{at} \cdot v_{at} = \frac{h}{\lambda_{dB}} \]

\( \lambda_{dB} \) units in de Broglie wavelength

Louis Victor de Broglie
Nobel prize 1929
Coherent splitting of atomic ensembles

**coherent** beam splitters and mirrors for light?

- glass plates, phase & absorption gratings
- metal or dielectric coatings

\[
S_1 \sim \cos (\phi_2 - \phi_1)
\]

\[
S_2 \sim \sin (\phi_2 - \phi_1)
\]
Coherent beam splitters and mirrors for atoms?

- atoms do not penetrate materials (apart from neutrons) & stick on surfaces
  
  coherent beam splitting by interaction with light

  momentum transfer = photon recoil due to exchange of photons

- interaction with gravitational, magnetic, electrostatic and electro-magnetic fields

  • light grating
  • adiabatic transfer
  • stimulated Raman transition

\[
\Delta \vec{v}_{at} = \frac{1}{M_{at}} \hbar \vec{k}_{Laser}
\]
Coherent splitting with stimulated Raman transitions

the mechanical effect of light:

- 2-photon transition between 2 long-lived hyperfine states
- manipulation of internal and external degrees of freedom

\[ \Delta \vec{v} = \frac{2}{m_{\text{atom}}} \hbar k_{Laser} \]
Optical components made out of light

\[ |e, +2 \hbar \kappa \rangle \]

\[ |g_1, 0 \hbar \kappa \rangle \]

\[ |g_2, +2 \hbar \kappa \rangle \]

\[ \langle g_2, +2 \hbar \kappa | g_2, +2 \hbar \kappa \rangle \]

\[ \langle g_2, +2 \hbar \kappa | g_1, 0 \hbar \kappa \rangle \]

\[ \langle g_1, 0 \hbar \kappa | g_2, +2 \hbar \kappa \rangle \]

\[ \pi / 2 - pulse \]

\[ \pi - pulse \]

\[ \pi / 2 - pulse \]

Excitation probability

pulse duration [\mu s]
Different types of light-pulsed induced coherent beam splitters

- Raman transition between two HF-ground states $|g\rangle \leftrightarrow |e\rangle$
- Multi-photon excitation between $|g\rangle \leftrightarrow |e\rangle$
- Multi-photon transition between same internal state $|g, p_0\rangle \leftrightarrow |g, p_0 + n\hbar k_{eff}\rangle$

\[ \pi/2 - \pi - \pi/2 \text{ pulse atom interferometer} \]

Cold Atom Sagnac Interferometer

Gyrooscope, Gravimeter, Gradiogravimeter

REALIZATION OF AN ATOM INTERFEROMETER WITH COLD ATOMS
π/2 - π - π/2 - pulse geometry

signal:

\[ \frac{N_{|g,p>}}{N_{|g,p>} + N_{|e,p+\hbar k_{eff}>}} \sim [1 + \cos(\phi_1 - 2\phi_2 + \phi_3 + \phi_{\text{inertial}} + \phi_{\text{non inertial}})] \]

[Full quantum mechanical description by C. Antoine, C. Bordé]
\[ \pi/2 - \pi - \pi/2 - \text{pulse geometry} \]

Determination of the exact trajectories gives the dominant contributions to the phase shifts induced by inertial forces:

- rotation \( d\phi_{\text{Rot}} = 2\Omega \cdot (\mathbf{k}_{\text{eff}} \times \mathbf{v}_a) T^2 \)
- acceleration \( d\phi_{\text{Bes}} = (a \cdot \mathbf{k}_{\text{eff}}) T^2 \)
- gradient of acceleration: \( (q \cdot \dot{\gamma} \cdot \mathbf{k}_{\text{eff}}) T^2 \)

signal:

\[ N_{|g,p>}/(N_{|g,p>} + N_{|e,p+hk>}) \sim [1 + \cos(\phi_1 - 2\phi_2 + \phi_3 + \phi_{\text{inertial}} + \phi_{\text{non inertial}})] \]

[Full quantum mechanical description by C. Antoine, C. Bordé]
\[ \pi/2 - \pi - \pi/2 - \text{pulse geometry} \]

\[ \implies \text{differential interferometry:} \]

\[ \text{rotation } d\phi_{\text{rot}} = 2\Omega \cdot (k_{\text{eff}} \times \mathbf{v}_{A})T^2 \rightarrow \quad d\phi_{\text{rot(source1)}} = -d\phi_{\text{rot(source2)}} \]

\[ \text{acceleration } d\phi_{\text{acc}} = (a \cdot k_{\text{eff}})T^2 \rightarrow \quad d\phi_{\text{acc(source1)}} = d\phi_{\text{acc(source2)}} \]

\[ \implies \text{distinguish between rotation and accelerations} \]

\[ \implies \text{reduction of common-noise} \]

(laser phase \( \phi_{i(source1)} = \phi_{i(source2)} \))

[Demonstrated by M. Kasevich, thermal Cs beam, PRL 78, 2046 (1997)]
Sagnac interferometer with cold atoms

... towards compact atomic Sagnac sensors

\[ \Delta \Phi_{\text{atoms}} = 2\pi \frac{2A}{L} \frac{m^2}{\hbar A} \cdot \Omega \]

- \( L \) = interferometer length
- \( v_T \propto \hbar k = \text{photon recoil} \) 1 cm/s
- \( A = L^2 \cdot \frac{v_T}{v_L} = \text{atomic launch velocity} \) 10,000 cm/s

\[ \frac{v_T}{v_L} \rightarrow 1 \]

\[ v_T \propto n_{Ph} \frac{\hbar k}{m} \]

\[ \frac{v_T}{v_L} \ll 1 \]
Sagnac interferometer with cold atoms

... towards compact atomic Sagnac sensors

\[ \Delta \Phi_{\text{atoms Sagnac}} = 2\pi \frac{2m_{\text{at}}}{h} A \cdot \Omega \]

\[ A = L^2 \cdot \frac{v_T}{v_L} \quad \rightarrow \quad v_T = \frac{\hbar k}{m_{\text{at}}} \quad \text{(constant)} \]

extension in length
+ quadratic effect
+ high cycle rate
- reduced stability

reduction in velocity
+ compact set-up
+ higher stability
- low cycle rate
Atomic versus laser gyroscopes

\[ \Delta \Phi_{\text{light}}^{\text{Sagnac}} = 2\pi \frac{2}{\lambda c} A \cdot \Omega \]

\[ \Delta \Phi_{\text{atoms}}^{\text{Sagnac}} = 2\pi \frac{2 m_{\text{at}}}{h} A \cdot \Omega \]

but: !!! \( \Delta \Omega (A,S/N) !!! \)
Comparison of different types of gyroscopes

<table>
<thead>
<tr>
<th></th>
<th>Wettzell (light)</th>
<th>Stanford (thermal Cs-atoms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>length [cm]</td>
<td>400</td>
<td>200</td>
</tr>
<tr>
<td>area</td>
<td>16m²</td>
<td>26mm²</td>
</tr>
<tr>
<td>sensitivity [rad.s⁻¹.Hz⁻¹/²]</td>
<td>9x10⁻¹¹</td>
<td>6x10⁻¹⁰</td>
</tr>
</tbody>
</table>

→\quad miniaturization possible by using cold atoms for interferometry
  - inertial sensitivity in 3 dimensions
    [B. Canuel, et al. PRL 97, 010402 (2006)]
  - better control of the atoms
    [T. Müller, et al. PRA 76, 063611 (Dec. 2007)]

→\quad transportable sensors based on cold atoms enable comparison and calibration of stationary systems
Realization with cold atoms

COLD ATOM SAGNAC INTERFEROMETER
**Interferometer scheme**

- Interferometry
- Detection
- Atom source 1
- Preparation
- Atom source 2

\[ 87\text{Rb} \ (|F=1, m_F=0> \ \& \ F=2, m_F=0>) \]

- Study of different interferometer topologies: pulsed / continuous
- Flexible source system (pulsed \( v_{At}=2.5-5\text{m/s} \))
- Expected resolution: \( \Delta \Omega \approx 2 \cdot 10^{-8} \text{ rad} \cdot \text{s}^{-1} \text{Hz}^{-1/2} \) (rotation)
  \[ \Delta a \approx 1 \cdot 10^{-8} \text{ ms}^{-2} \text{Hz}^{-1/2} \) (acceleration)

Experimental realisation
Steps towards an atom interferometer

Basic components of the atom interferometer

→ atomic source
→ preparation
→ interferometry
→ detection
Basic components of the atom interferometer

Atomic source
Atomic Source

2D-MOT:
- High flux ($10^{10}$ at/s) of slow-moving atoms ($v \sim 15$ m/s)
- 3D-MOT loading-rate $5 \times 10^9$ at/s

3D-MOT/ moving molasses:
- $10^8$ atoms in 3D-MOT after 20 ms loading time

- moving molasses: $T = 8$ µK, $v \sim 2.8$ m/s
- relative uncertainty of $v_{\text{at}} \sim 3 \times 10^{-4}$ → rotation uncertainty of $5 \times 10^{-9}$ rad/s (@1s)

Basic components of the atom interferometer

Preparation

state and velocity selective
Preparation - *state and velocity selection*

Preparation of atoms in: $|F=1, m_F=0>$

1. 
   - $|F=2>$ to $|F'=2>$ ($\pi$ - polarised light) 
   - simultaneously: repumper $|F=1>$ to $|F'=2>$ 
   - atoms in $|F=2, m_F=0>$ 
   - repumper later off than pumper 
   - all atoms in ground state $|F=2>$, most of them in $|F=2, m_F=0>$

2. 
   - Raman $\pi$-pulse - **velocity filter**
     - $|F=2, m_F=0>$ to $|F=1, m_F=0>$

3. 
   - „blow-away“ $|F=2>$ to $|F'=3>$ removes atoms in $|F=2>$
Basic components of the atom interferometer

Interferometry
Interferometry

- Two photon Raman-transition

High phase stability of the Raman-lasers necessary:

- Digital phase – lock of two diode lasers
  - \( v_0 = 6,834 \ldots \text{GHz} \), lock bandwidth \( \sim 3 \text{MHz} \)
  - estimated phase error \( \Delta \phi \sim 40 \text{mrad} \)

- Coupling of the \( m_F=0 \) – sub-states
  \( (\sigma^+ - \text{polarised in homogeneous B-field}) \)
Basic components of the atom interferometer

Detection
Detection

State-selective fluorescence detection: |F=1⟩ and |F=2⟩ (not selective to |m_F⟩)

1. Detection of |F=2⟩ via transition: |F=2⟩ to |F’=3⟩
2. Transfer of atoms from |F=1⟩ to |F’=2⟩
3. Detection of all atoms via transition: |F=2⟩ to |F’=3⟩
4. Additionally: detection of background scattered light

\[ \text{fraction } N_{|F=2⟩}/(N_{|F=2⟩}+N_{|F=1⟩}) \approx [1 + \cos(\phi_{\text{laser}} + \phi_{\text{inertial}})] \]
Steps towards an atom interferometer

Interferometry measurements

- Different interferometry topologies
**Single pulse measurements / velocity-selective configuration**

**Rabi oscillations:**
- Experimental optimization of pulse parameters
- Excitation efficiency: \( \sim 50\% \)

**Raman spectroscopy:**
- Temperature measurements
- Optimization of velocity-selective state preparation

![Graph showing Raman pulse duration vs. transition probability]

![Graph showing frequency vs. transition probability]
Two simultaneously operated Ramsey-interferometers

- Cancellation of the light shift
- Magnetic field measurement
- AC-Stark shift compensation
\( \pi/2 - \pi - \pi/2 \) – pulse atom interferometer / velocity-selective configuration

Sweep of laser phase before last beam splitter pulse \( \rightarrow \) interferometer fringes

### Interferometer results:
- \( \rightarrow \) Contrast: 37.9\%
- \( \rightarrow \) S/N: 45.5
- \( T = 0.5 \text{ ms}, \tau_\pi = 10\mu\text{s} \)

\[(\Delta \Omega)^2 = (\Delta \varphi)^2 / (\frac{\partial \varphi}{\partial \Omega})\]

**Minimising phase noise**

- Increasing number of atoms
- Beating the shot noise
- Environmental control \( \rightarrow \) Space
- Ultrastable lasers (frequency, intensity)

- Large area
- Long interaction times
  \( \rightarrow \) Large atomic mass
  \( \rightarrow \) Space
- Ultra cold atoms
- Coherence
Realization with cold atoms

GYROSCOPE
GRAVIMETER
GRAVITY GRADIOMETER
Gyroscope – GOM by A. Landragin

- Cs-atoms, $T = 2.5 \, \mu \text{K}$
- steep-parabolic trajectories for atomic clouds
- Raman-transition for interferometry (single window)

intended resolution: \[ \Delta \Omega \approx 4 \cdot 10^{-8} \, \text{rad} \cdot \text{s}^{-1} \cdot \text{Hz}^{-1/2} \]
\[ \Delta a \approx 4 \cdot 10^{-8} \, \text{m} \cdot \text{s}^{-2} \cdot \text{Hz}^{-1/2} \]

determination of earth's rotation:
\[ 5.50 \pm 0.05 \times 10^{-5} \, \text{rad/s} \] (accuracy of 1%)

[P. Cheinet, B. Canuel, F. Pereira Dos Santos, A. Gauguet, F. Yver-Leduc, and A. Landragin, IEEE 57 (6), 1141 (2008)]
A six-axis inertial sensor with cold atoms

- butterfly configuration: $\pi/2 - \pi - \pi - \pi/2$

- sensitive for detecting $\Omega_{x,y,z}$ and $a_{x,y,z}$

Gravimeter – by A. Landragin

- Measurement of acceleration of gravity \( g \)
- intended accuracy: \( \Delta g/g < 10^{-9} \)
- present sensitivity: \( \Delta a \approx 1.4 \times 10^{-8} g.Hz^{-1/2} \)

Application:

Watt balance experiment

→ Definition of kg requires knowledge of \( g \)
Verification of the equivalence principle with an atom interferometer:

- comparing the free fall of e.g. Cesium and Rubidium atoms in earth orbit
- determining the phase shift:

Testing General Relativity with Atom Interferometry
Savas Dimopoulos, Peter W. Graham, Jason M. Hogan, and Mark A. Kasevich
Department of Physics, Stanford University, Stanford, California 94305
(Dated: October 11, 2005)

The unprecedented precision of atom interferometry will soon lead to laboratory tests of general relativity to levels that will rival or exceed those reached by astrophysical observations. We propose a test based on gravitational redshift, which is a general relativistic effect better than the current limit, and in fact in $10^{-7}$ in the future. It will also probe general relativistic effects such as non-linear three-graviton couplings, the geometry of an atom's kinetic energy, and the falling of light—to several decimals. Further, in contrast to astrophysical observations, laboratory tests can isolate these effects via their different functional dependence on experimental variables.
Gravimeter – by M. Kasevich

Precision gravimetry and test of the Equivalence Principle with a 10-meter atomic gravimeter.

High precision derives from using light pulse atom interferometry over a 10-meter baseline.

Projected Sensitivity: \[ \delta g < 10^{-15} g \]

Applications:

- Equivalence Principle test
- General Relativistic effects in the lab
- Atom charge neutrality
- Gravitational wave detection

Evaporatively cooled atom source

10 m atom drop tower
Gravity gradiometer – MAGIA by G.Tino

\[ G = 6.667 (0.003) \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2} \]

\[ G = 6.693 (0.027) \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2} \]

[M. Kasevich group 2007]

[G. Lamporesi, A. Bertoldi, L. Cacciapuoti, M. Prevedelli, and G. M. Tino, PRL 100, 050801 (2008)]
Summary

- Inertial measurements by cold atom interferometry offer unprecedented high precision and compactness

- First fields of application are explored
  - General relativity and gravity, navigation, inertial references, Earth observation, geodesy, geology, ...
  - Further development towards final sensitivity

→ Experiments in space
Thank You