Atom interferometry in microgravity: the ICE project

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21/10/09 Workshop GPhyS, Les Houches
The ICE project: testing the UFF with a two-species atom interferometer in microgravity

- **The idea:** an atom-interferometric measurement of the local differential acceleration between two atomic species ($^{39}$K and $^{87}$Rb).

- **Microgravity:** longer interrogation times

- **Important technological aspect:** compactedness, design of new laser sources,...
Wave packets manipulation with Raman transitions

Raman transition: coherent transfer between the two fundamental hyperfine states using optical wavelengths.

\[ \phi_1, \omega_1, k_1 \rightarrow \phi_2, \omega_2, -k_2 \]

\[ \varphi_{\text{eff}} = \phi_1 - \phi_2 \]

\[ k_{\text{eff}} = k_1 - k_2 \]

Laser phase printed on the atomic wave during a transition.
Atom interferometer as an inertial sensor

Mach-Zehnder configuration

Acceleration

\[ \Delta \phi = k_{\text{eff}} \cdot g \cdot T^2 \]

Measured by the population ratio at the output of the interferometer
Increasing the interrogation time

- Different solutions:
  - Atomic fountain ($T \approx 800$ ms).
  - 10 meter high interferometer (Stanford): $T \approx 1.4$ s
  - Parabolic flights (ICE): $T \approx 20$ s, $10^{-2}$ g.
  - 100 m drop tower in Bremen (QUANTUS): $T \approx 5$ s, $10^{-6}$ g.
  - Satellite (PHARAO).

Need for a compact and/or transportable interferometer
Ballistic flights for microgravity

- In the Novespace A300 ZERO-G Airbus (Bordeaux airport)
- 31 parabolas per day for 3 days
- \( \approx 30 \text{ minutes of micro-g (}10^{-2}\text{ g)}\)

But noisy environment!

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Setup

A full cold atom experiment in 3 parts
(650 Kg, 1500 W)

Electrical panel + High laser power

μ-wave reference, laser sources, computer, etc...

Science cell
(in its magnetic shield)

21/10/09
Workshop GPhyS, Les Houches
Laser sources for $^{87}\text{Rb}$

- Based on telecom technologies → reliable, robust and compact system with fiber components.
- Relies on Second Harmonic Generation (cooling frequency for $^{87}\text{Rb}$: 780 nm = 1560 nm / 2)

**Frequency generation**

![Diagram of laser sources for $^{87}\text{Rb}$]

- Master laser
  - DFB
  - OI
  - PPLN WG
  - Pd
  - Beat note
  - 1560 nm
- Slave laser
  - DFB
  - OI
  - Pd
  - MZ
  - $\approx 6.8$ GHz
  - Towards EDFA

**Sideband generation (MOT/Raman)**
Free-space doubling stage

- Possibility to make a MOT or Raman transition with the same setup.
- About 120 mW after the optical fibers
The science cell

- MOT: 3 retro-reflected beams provided by a 1-to-3 fiber beam splitter (Schäfter-und-Kirchoff)
- Raman beams: horizontal
- Atom detection by fluorescence with the MOT beams

→ reduced T.O.F. (on Earth at least) but compact interferometer

**Experimental sequence used for Ramsey fringes on Earth**

No more than $T=25$ ms on Earth for us

21/10/09
October 2008 flight session:
Ramsey fringes with copropagating Raman transitions

• Not sensitive to inertial effects.

\[ \Omega_{\text{eff}} \approx 2\pi \times 12.5 \text{ kHz} \]
On Earth vs microgravity (T=40 ms)

MOT

Raman sequence

Detection

No normalization

Transition probability (a.u.)

Frequency (GHz)

0 g (T=40ms)

1 g (T=40ms)
On Earth vs microgravity (T=40 ms)

MOT

Raman sequence

Detection

No normalization

Transition probability (a.u.)

0 g (T=40ms)

1 g (T=40ms)

Frequency (GHz)
Results in microgravity

- One point = one shot
- One scan per parabola
- Limited by temperature

Retroreflected geometry:

- Copropagating transitions limited by appropriate polarization of beams.
- Limitation of wave-front aberrations.
- Sensitive to acceleration, but also to vibrations on the retroreflecting mirror.
**Acceleration noise**

- The ZERO G Airbus is a very noisy environment \((10^{-2} \text{ m.s}^{-2})\)
- Vibrations induce a displacement \(\delta_x\) of the mirror:

\[
\phi_{raman} = \phi_1 - \phi_2 + \delta \phi
\]

with \(\delta \phi \propto k_2 \delta_x\)

If \(\delta_x\) changes too much during the interferometer sequence, no interference pattern is visible.
Reduction of vibration noise

- The acceleration noise is read with an accelerometer.
- Active suspension of a mirror mounted on piezoelectric actuator.
- Developed by Cedrat under CNES contract.

But it doesn’t work as well as expected for frequencies < 10 Hz

Not suitable for the plane

(used in open-loop...)

21/10/09 Workshop GPhyS, Les Houches
October 2009 flight session (last week):

Mach-Zehnder interferometer

Scanning the phase in µg:

- No vibration isolation.
- Phase jumps between the last pulses to scan an interference fringe.
- **Nothing visible for T>250 µs**
• We still have Raman transitions after 80 ms of time of flight

Atoms are still here: interest of microgravity
Atomic accelerometry in microgravity

- Correlation between the vibration noise of the mirror (read by the accelerometer on the retroreflected mirror) and the atomic population ratio after the interferometry sequence.

  $\Rightarrow$ Acceleration sensitive

- Nothing visible for $T>500$ µs.

- Perhaps limited by the Cedrat accelerometer noise...

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Next campaign: A two-species atom interferometer

- **The idea:** An atom-interferometric measurement of the local differential acceleration between two atomic species ($^{39}\text{K}$ and $^{87}\text{Rb}$).

- Extraction of the differential acceleration from the interferometric signal using Bayesian statistical estimation.

- Differential measurement: Possibility of a common-mode rejection on the acceleration noise.

- Full process explained in details in G. Varoquaux *et al.*, N. J. Phys., to be published

  arXiv:0910.2412v1
Why $^{39}\text{K}$?

- Large mass ratio and very different nuclear compositions.
- Isotopic abundance.
- Interesting wavelength.

$767 \times 2 = 1534$ nm

Telecommunications C-band technologies

Same idea as for Rb
A differential measurement

\[
\begin{align*}
\phi_{Rb} &= k_{Rb} a_{Rb} T_{Rb}^2 \\
\phi_K &= k_K a_K T_K^2
\end{align*}
\]

2 atomic interferometers such as:

\[
k_{Rb} T_{Rb}^2 = k_K T_K^2
\]

Ration of population

Interferometric phase

Phase and acceleration noises

Reduction of the influence of vibration noise (common mode rejection)

Differential phase: \( \delta \phi = \phi_K - \phi_{Rb} \)
Differential phase estimation

- Use of a Bayesian estimator for the differential phase.
- Fast convergence (<30 meas.).

Expected performances:

For $\sigma_X = 1\ \mu m$, after 30 data points, $\delta\phi \approx 30\ mrad$

$$\eta = \frac{\Delta a}{a} \approx 5 \cdot 10^{-11}$$
for $T=2s$
Conclusion/prospects

- There is a transportable atomic interferometer but limited by acceleration noise.
- Microgravity is a good candidate for long interrogation time.
- Most challenging point (for the moment...): **vibration isolation!!**

Next steps:

- Interferometer with K (evaporative cooling in a dipole trap at 1565 nm).
- Double interferometer with Rb and K: test of the UFF.
- Extrapolation to an inertial sensor on dedicated orbital platform (rough estimation):

\[ \eta < 5 \times 10^{-14} \]

(integration over 1 year)
Thank you for your time