Atomic Quantum Sensors and Fundamental Tests

C. Salomon
Laboratoire Kastler Brossel, Ecole Normale Supérieure, Paris
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Fundamental Questions

1) Missing mass in the Universe
   Dark matter and dark energy represent 95% of the mass of the Universe but have unknown origin!
   New particles and/or change of the laws of gravity?

2) Atomic Sensors can test fundamental laws with exquisite precision
   Einstein’s equivalence principle and Universality of Free Fall
   Tests of gravity in Earth orbit or at solar system scale
   Precision redshift measurement
   Variability of fundamental constants

3) Quantum sensors have societal applications
   Accelerometry, Gravimetry, Navigation, GPS, GALILEO, Geodesy, Earth monitoring,…
Atom Interferometry

Matter wave interferometry: as old as Quantum Mechanics
Cold atoms: new opportunities with large De Broglie wavelength

Atomic Source → Beam splitter → Beam recombinder → DETECTOR

Change of optical path-length...
Atom interferometry

Atomic source
Beam splitters
Detectors

Change of phase of interference pattern
Atoms have internal states
Two level atom: g, e
Laser resonant on g-e transition

Neglect spontaneous emission
Use long lived upper states
Mg, Ca, Sr, Yb, …
or
Raman Transition between
hyperfine ground states
in alkalis for instance

Effective two-level system
Matter-wave sensors and precision measurements

Clocks and Interferometers

T: interaction time with ELM field
Slow atoms: T large; atomic fountain or microgravity
Trapped atoms: T large
Clocks: gain prop. To T

Inertial sensors:
Accelerometers: gain as $T^2$
Sagnac gyrometers: gain as $LT$

Current sensitivity:
Acceleration: $\delta g/g = 1.4 \times 10^{-8}$ in 1s
Rotation: $\Omega = 6 \times 10^{-10}$ rad s$^{-1}$ in 1 s

Clocks:
Frequency stability: $\delta v/v = 2 \times 10^{-15}$ in 1s
Accuracy: $= 8.6 \times 10^{-18}$
Mach-Zehnder interferometer with light beams

\[ |g, p\rangle \]

\[ |e, p + \hbar k\rangle \]

Sensitivity to rotation and accelerations: gyrometers and gravimeters

\[ \delta \phi = \phi_1(t_0) - 2\phi_2(t_1) + \phi_3(t_2) \]
\[ \delta \phi = -k_{eff} a T^2 = -k_{eff} g T^2 = -2k_L g T^2 \]

**Ground sensitivity:** \( \sigma_g \sim 10^{-7} \text{ m.s}^{-2} \) at 1s

with interrogation time 100 ms limited by vibrations

**Extrapolation to space:** <10^{-10} \text{ m.s}^{-2} at 1s

with interrogation time 2 s

**With ultra-cold atoms:** \( \sim 10^{-11} \text{ m.s}^{-2} \) at 1s

with interrogation time 10 s

Earthquake in China 2 Mars 20\textsuperscript{th} 2008 (magnitude 7.7)
BEC in microgravity: QUANTUS

Coordinator E. Rasel

Exploring coherent matter waves at lowest energy scales, in particular for

... Precision inertial sensing

... Quantum test of the principle of equivalence beyond 1 part in $10^{15}$

Atomic wave packet delocalised over 1 mm
Achievements:
- > 170 drops
- Robust alignment
- 3 drops per day
- High complexity
- Study of Evolution & control of condensates

Goals:
- Test of chip-based and all-optical atom lasers for precision inertial sensing
- Atom interferometry coherent matter waves
- Test of free fall of isotopes of potassium and rubidium
ICE: Atom accelerometer in microgravity
Coordinator P. Bouyer

• Operation of atom interferometer in the 0g airbus.

• Demonstration of atom accelerometer in weightlessness.
  • Demonstrated background vibration suppression by correlation measurement of atom & classical accelerometer.

2 species atom interferometer : test of the equivalence principle @ 10^{-11} in the plane and 10^{-13} on ISS.
SAI - Space Atom Interferometer
Coordinator: Guglielmo M. Tino
Main goal: compactness/portability -> to fit into a drop-tower capsule

- Use same cell for trapping and detection (launch in 1-1-1 config.)
- HUB design for titanium vacuum cell
- Load 3D-MOT from 2D-MOT
- Magnetic shield on whole vacuum system
- Launch into a 20 cm tube
- Single axis Raman accelerometer
- Sensitivity spec $3 \times 10^{-7} \text{ m/s}^2 \ @ \ 1\text{s}$
Quantum sensors (2)

Cold Atom Clocks
The precision of time has improved significantly over the years, from the astronomical and mechanical era to modern optical clocks. Historically, clocks have relied on natural phenomena like the pendulum and quartz, but the advent of atomic clocks and GPS has brought unprecedented accuracy. The graph illustrates the progress in timekeeping, with the y-axis representing clock uncertainty in seconds per day and the x-axis showing the year. The precision of time has advanced from 100 ps/day to 10 ps/day, and ultimately, to 1 ps/day with the use of optical clocks.
In Space: Cold Atom Clock in $\mu$-gravity: PHARAO/ACES

Same Technology can be applied to matter wave sensors
To be launched to ISS in 2013

- A cold atom Cesium clock in space
- Fundamental physics tests
- Worldwide access
Trapped-atom clock on a chip

$87\text{Rb}: (I = \frac{3}{2})$

$F = 2, \ m_F = +1$

$F = 1, \ m_F = -1$

experience same trapping potential (same magnetic moment)

$N \sim 3 \times 10^4$ atoms

$T \sim 200 \text{ nK}$

$d \sim 150 \mu\text{m}$ atom-surface distance

result: $\tau \sim 17 \text{ s}$ coherence lifetime

P. Rosenbusch, J. Reichel, SYRTE-ENS, 2009
2 Families of Optical Clocks: Trapped Ions and Neutral Atoms

- Quality of the clock: $\frac{\nu}{\Delta \nu} \times \text{S/N} = 2 \nu T \times \text{S/N}$
- Increase the frequency, increase $T$, increase S/N
- Trapped ions: $T$ very long but only one (few) ion in the trap.
- Neutral atoms: $T$ long and large numbers: improved stability
  - NIST: Rosenband et al.
  - Al$: \text{optical transition}$
  - Accuracy: $8.6 \times 10^{-18}$
  - A factor of 30 beyond the cesium accuracy!

- Neutrals: Ca, Sr, Yb, Mg, Hg, ...
- Sr: $10^{-16}$ accuracy, Ye et al.
- TOKYO, JILA, SYRTE, PTB, FLORENCE, ..
Goal: develop optical lattice clocks with inaccuracy at $10^{-17}$ level for space applications, in particular on ISS. Two approaches: Strontium and Ytterbium

Pre-Phase A project (2007-10): $1 \times 10^{-16}$ on Sr clocks, development of compact subsyst.

Current status on stationary Sr clocks: Study of systematic effects at $10^{-16}$ level, Frequency instability $<1 \times 10^{-15}$, transition linewidth 9 Hz, non-destructive detection

Transportable Yb clock system
all-diode laser based. Current status: routine operation of 2nd stage cooling, 2 Hz linewidth clock laser

Sr breadboard with modular subsystems and all-fiber light delivery. Current status: atomic beam production; transp. Sr clock laser with $<10$ Hz linewidth
Space Optical Clocks (Phase 2, 2010-14)

• **Goal:** Building on SOC-I results, develop transportable/breadboard lattice clocks with \(5 \times 10^{-17}\) inaccuracy, < \(1 \times 10^{-15}/\tau^{1/2}\) instability (Sr, Yb).

• 2\(^{nd}\) generation breadboard Sr atomic and electrooptics system: < 170 kg, 1000 liter.

• Modular systems
  • Develop reliable, compact and rugged lasers and subsystems
  • Advanced atomic chambers, optimized w.r.t. size, black-body shift
  • Transport and characterization of clocks at national metrology labs (PTB, INRIM)

• Laser diode reliability tests; compact frequency comb development

• 16 partners
Future Time Definition from Space

1) The Earth gravitational potential fluctuations will limit the precision of time on the ground at $10^{-18}$-$10^{-19}$ (ie: cm to mm level)

2) The only Solution: set the reference clocks in space where potential fluctuations are vastly reduced

3) Improved Navigation, Earth Monitoring and Geodesy

4) Interesting for fundamental physics Tests
Mission opportunities with clocks

General Relativity test improvement wrt GPA

- PHARAO: $1 \times 10^{-16}$ inaccuracy; $1 \times 10^{-13}/t^{1/2}$ instab.
- Optical clock: $10 \times$ in accuracy, $100 \times$ more stable

Redshift test at Mercury with $5 \times 10^{-10}$ inaccuracy
second-order grav. red-shift + Shapiro time delay @ $10^{-8}$

Cost, complexity

PHARAO + ISS

Optical clock + ISS

PHARAO + Earth orbit

Optical clock + Earth orbit

PHARAO + trajectory towards sun

Optical clock + trajectory tow. sun
The SAGAS Project

test of gravity at solar system scale

Test body trajectory + light trajectory + proper time

= Measures all aspects of gravity!

arXiv: 0711.0304, (2008);
peter.wolf@obspm.fr
Matter-wave interferometers and cold atom clocks have entered into high precision measurement phase

Technology has progressed fast with routinely working instruments
Fine structure constant $\alpha \approx 3 \times 10^{-9}$
Clocks reach stabilities and accuracies in the sub $10^{-17}$ range

Impressive efforts for miniaturization and reliability
Compact laser sources and atom chips
quantum gases sources: BEC in microgravity and atom lasers

Beyond ACES on the ISS (2013-2015)
Optical Clocks with $10^{-17}$ frequency stability in 2019 on the ISS or satellite
Test of Equivalence Principle in Space with quantum objects beyond $10^{-15}$
Precise accelerometry demonstration

High precision clocks can bring tests of the laws of gravitation to a new level of precision
Coordinated action between ESA directorates is important!