Detecting gravitational waves with atomic sensors

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Les Rencontres de Physique de la Vallée d'Aoste
Results and Perspectives in Particle Physics
La Thuile, 26/2/2018
Laser cooling: Optical molasses

\[ \nu_L(1-\nu/c) \quad \nu_L(1+\nu/c) \]

Lab ref. frame
Atom ref. frame

\[ \nu \]

\[ e \]

\[ f \] \[ \delta \] \[ \nu_{at} \]

\[ \nu_{at} > \nu_L \]

Atomic Temperature: \[ k_B T = Mv^2_{\text{rms}} \]

Doppler limit:
\[ k_B T_D = \frac{\hbar \Gamma}{2} \]

Recoil limit:
\[ k_B T_r = \frac{1}{M} \left( \frac{\hbar \nu_L}{c} \right)^2 \]

Examples:

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<th>( T_D )</th>
<th>( T_r )</th>
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<tbody>
<tr>
<td>Na</td>
<td>240 ( \mu K )</td>
<td>2.4 ( \mu K )</td>
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<tr>
<td>Rb</td>
<td>120 ( \mu K )</td>
<td>360 ( nK )</td>
</tr>
<tr>
<td>Cs</td>
<td>120 ( \mu K )</td>
<td>200 ( nK )</td>
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<tr>
<td>Sr</td>
<td>180 ( nK )</td>
<td>460 ( nK )</td>
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</table>

Idea: T.W. Hänsch, A. Schawlow, 1975
Exp. demonstration: S. Chu et al., 1985
Sr Magneto-Optical Trap (MOT)
LENS - Firenze
Atom interferometry
Wave-particle duality in quantum physics

\[ \lambda_{dB} = \frac{h}{Mv} \]

de Broglie wavelength


Alexander D. Cronin, Jörg Schmiedmayer, David E. Pritchard, Optics and interferometry with atoms and molecules, Rev. Mod. Phys., Vol. 81, No. 3 (2009)

Atom interferometry
and gravity
MAGIA
(Misura Accurata di G mediante Interferometria Atomica)

- Measure $g$ by atom interferometry
- Add source mass
- Measure change of $g$

➢ Precision measurement of $G$

$$F(r) = G \frac{M_1 M_2}{r^2}$$
MAGIA

Rb gravity gradiometer + source mass

Sensitivity $10^{-9}g/\text{shot}$

one shot $\Rightarrow \Delta G/G \approx 10^{-2}$

Peak mass acceleration $a_G \approx 10^{-7}g$

10000 shots $\Rightarrow \Delta G/G \approx 10^{-4}$

500 kg tungsten mass
Precision measurement of the Newtonian gravitational constant using cold atoms

G. Rosi¹, F. Sorrentino¹, L. Cacciapuoti², M. Prevedelli³ & G. M. Tino⁴

About 300 experiments have tried to determine the value of the Newtonian gravitational constant, \( G \), so far, but large discrepancies in the results have made it impossible to know its value precisely. The weakness of the gravitational interaction and the impossibility of shielding the effects of gravity make it very difficult to measure \( G \) while keeping systematic effects under control. Most previous experiments performed were based on the torsion pendulum or torsion balance scheme as in the experiment by Cavendish in 1798, and in all cases macroscopic masses were used. Here we report the precise determination of \( G \) using laser-cooled atoms and quantum interferometry. We obtain the value \( G = 6.67191(99) \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2} \) with a relative uncertainty of 150 parts per million (the combined standard uncertainty due to the relevant gravitational signal. An additional cancellation of common-mode spurious effects was obtained by reversing the direction of the two-photon recoil used to split and recombine the wave packets in the interferometer. Efforts were devoted to the control of systematics related to atomic trajectories, the positioning of the atoms and effects due to stray fields. The high density of tungsten was instrumental in maximizing the signal and in compensating for the Earth’s gravitational gradient in the region containing the atom interferometers, thus reducing the sensitivity of the experiment to the vertical position and size of the atomic probes.

The atom interferometer is realized using light pulses to stimulate \(^{87}\text{Rb} \) atoms at the two-photon Raman transition between the hyperfine levels. The Doppler broadening of the beams and the interaction time were measured with an accuracy of 1 part in 30,000. The atom cloud was confined using a combination of optical and magnetic traps to minimize the effects of stray fields.

\[
G = 6.67191(77)(62) \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}
\]

Relative uncertainty: 150 ppm

G. Rosi, F. Sorrentino, L. Cacciapuoti, M. Prevedelli & G. M. Tino,

Precision Measurement of the Newtonian Gravitational Constant Using Cold Atoms

NATURE vol. 510, p. 518 (2014)
Ultracold Sr - Experiments in Firenze

- Optical clocks using visible intercombination lines


- New atomic sensors for fundamental physics tests


Optical clocks: Towards $10^{-18}$

- Narrow optical transitions
  $\delta\nu_0 \sim 1$-$100 \text{ Hz, } \nu_0 \sim 10^{14}$-$10^{15} \text{ Hz}$

\[
\sigma_y \approx \frac{\text{Noise}}{\pi Q \cdot \text{Signal}} \approx \frac{\Delta \nu}{\nu_0} \frac{1}{\sqrt{N_{\text{atom}}}} \sqrt{\frac{T_{\text{cycle}}}{2\pi \text{average}}} \frac{1}{C_{\text{fringe}}}
\]

- Candidate atoms
  - Trapped ions: Hg$^+$, In$^+$, Sr$^+$, Yb$^+$, …
  - Cold neutral atoms: H, Ca, Sr, Yb, …

- Direct optical-$\mu$wave connection by optical frequency comb

Th. Udem et al., Nature 416, 14 March 2002
Microwave vs. optical clocks

Measure gravitational red shift in the lab

Bloch oscillations of Sr atoms in an optical lattice
Precision gravity measurement at µm scale

\[ \nu = m g \lambda / 2h \]


Bloch oscillations of $^{88}\text{Sr}$ atoms

N. Poli, F.Y. Wang, M.G. Tarallo, A. Alberti, M. Prevedelli, G.M. Tino,
Precision Measurement of Gravity with Cold Atoms in an Optical Lattice and Comparison with a Classical Gravimeter,
Detection of Gravitational Waves by Atom Interferometry

Main ideas

• Detection of GWs by matter waves
• Drastic reduction of critical noise sources
• Addressing new interesting frequency ranges
Can we use atom interferometers in searching for gravitational waves?

- C.J. Bordè, University of Paris N.
- G. Tino, University of Firenze
- F. Vetrano, University of Urbino

• R.Y. Chiao, A. D. Speliotopoulos, “Towards MIGO, the matter-wave interferometric gravitational-wave observatory, and the intersection of quantum mechanics with general relativity”, Journal of Modern Optics (2004), 51(6-7), 861-899


• A. Roura, D.R. Brill, B. L. Hu, C.W. Misner, W.D. Phillips, “Gravitational wave detectors based on matter wave interferometers (MIGO) are no better than laser interferometers (LIGO)”, Physical Review D: Particles and Fields (2006), 73(8), 084018/1-084018/14

• G.M. Tino, F. Vetrano, "Is it possible to detect gravitational waves with atom interferometers?", Class. Quantum Grav. 24, 2167 (2007)

Gravitational Waves Detection with Atom Interferometry

Conference

Organizers:
Guglielmo M. Tino, University of Firenze, Italy
Flavio Vetrano, University of Urbino, Italy

Period from 22-02-2009 to 24-02-2009
Deadline: 15-01-2009

Notes: The number of participants is limited to 50. The participation fee for the Workshop is 150 Euros including registration, coffee-breaks, lunches and the social dinner. The fee should be paid cash on arrival at the registration desk.

Abstract
The possibility of using atom interferometers to detect gravitational waves is attracting increasing interest as an alternative to other detectors. Several papers were published discussing theoretical and experimental aspects. Although the results show that dedicated technological developments are still needed to achieve the required sensitivity values which are beyond those presently available, new schemes for atom interferometers, beam splitters and high flux coherent atomic sources could lead to an increase in sensitivity and make atom interferometers competitive with other gravitational wave detectors. The Workshop on “Gravitational Waves Detection with Atom Interferometry” will bring together scientists interested in theoretical and experimental aspects to discuss different ways of improving atom interferometers for gravitational wave detection.

Special issue on
Gravitational Waves Detection with Atom Interferometry
G.M. Tino, F. Vetrano, C. Laemmerzahl Editors,
General Relativity and Gravitation 43, 1901 (2011)
Gravitational waves detection with atom interferometry

• **Single atom interferometer**


• **Differential scheme**

Laser frequency noise insensitive detector


- Long-lived single photon transitions (e.g. clock transition in $^{87}\text{Sr}$, Ca, Yb, Hg, etc.).
- Atoms act as clocks, measuring the light travel time across the baseline.
- GWs modulate the laser ranging distance.

from M. Kasevich
STANFORD UNIVERSITY
Gravitational wave detection with clocks

\[ \sigma(\tau) = \frac{\delta \nu}{\nu_o} \bigg|_{\tau} = \frac{\sqrt{\Delta_A}}{\nu_o \sqrt{2\pi \tau N}} \]

from J. Ye

S. Kolkowitz, I. Pikovski, N. Langellier, M.D. Lukin, R.L. Walsworth, J. Ye,
Proposal title

SPACE ATOMIC GRAVITY EXPLORER

Acronym

SAGE

Lead Proposer

Prof. Guglielmo M. Tino

Dipartimento di Fisica e Astronomia and LENS Laboratory, Università di Firenze
Istituto Nazionale di Fisica Nucleare
Firenze (Italy)

In response to the Call for New Science Ideas in ESA’s Science Programme

September 13, 2016
We consider a multi-satellite configuration with payload/instruments including Strontium optical atomic clocks, Strontium atom interferometers and satellite-to-satellite/satellite-to-Earth laser links.

SAGE main scientific goals are:

**PRIMARY GOAL:**
- Observe Gravitational Waves in new frequency ranges with atomic sensors.

**SECONDARY GOALS:**
- Search for Dark-Matter
- Measure the Gravitational Red Shift
- Test the Equivalence Principle of General Relativity and search for spin-gravity coupling
- Define an ultraprecise frame of reference for Earth and Space and compare terrestrial clocks
- Investigate quantum correlations and test Bell inequalities for different gravitational potentials and relative velocities
- Use clocks and links between satellites for optical VLBI in Space

Although the technology for such a mission is not mature yet, it takes advantage of developments for the ACES (Atomic Clock Ensemble in Space) mission and the results of ESA studies for SOC (Space Optical Clock), SAI (Space Atom Interferometer), STE-QUEST, GOAT and ongoing national projects in this frame.

Supporting scientists and institutes from ESA member states as well as from USA, China, Japan, Singapore are listed in the final section of the proposal.
SAGE: GW detection

![Graph showing strain sensitivity vs frequency for different gravitational wave detectors. The graph compares SAGE, SAGE-Al, SAGE-Clocks, eLISA, Advanced Virgo, Advanced LIGO, EMRI, MBHB, NSB, CBI, and RGB.]
SAGE: Search for Dark-Matter

(Left) An atomic clock sweeps through the DM. DM is assumed to be composed of extended objects (or clumps). If there is a difference of fundamental constants (such as the fine-structure constant in the figure) inside and outside the clumps, the clumps can cause the clock to slow down or speed up [A. Derevianko and M. Pospelov. Hunting for topological dark matter with atomic clocks. Nature Phys., 10:933, 2014].

Atom interferometry with the Sr optical clock transition

- $^{88}$Sr isotope
- $B=300$ G $\rightarrow \Delta \nu=20 \mu$Hz
- Rabi frequency $\Omega \sim 1\text{kHz}$

Liang Hu, Nicola Poli, Leonardo Salvi, Guglielmo M. Tino,
Atom interferometry with the Sr optical clock transition,
SAGE: SPACE ATOMIC GRAVITY EXPLORER
Strontium Atomic Interferometers and Clocks in Space for Fundamental Physics and Applications

Firenze, 2011
MAGIA ➟ MAGIA-Adv

Advanced atomic quantum sensors for gravitational physics

• Large-scale atom interferometer (Rb & Sr)

• New schemes for large momentum transfer

• High-flux atomic sources

• High-sensitivity detection schemes

• Squeezed atomic states

• Sezioni: Firenze (+Urbino), Pisa
Shot noise limited (diff. configuration)

\[ h_{\text{rms}} = \frac{1}{2nkL \sin^2(\omega T/2)\sqrt{\eta}} \]

- MAGIA (L=0.5m, T=0.3 s, n=1, \( \eta = 10^5 \text{s} \))
- MAGIA upgraded (L=0.5m, T=0.3 s, n=10, \( \eta = 10^8 \text{s} \))
- 10 m demonstrator (L=5m, T=1 s, n=100, \( \eta = 10^{12} \text{s} \))
- 100 m detector (L=50m, T=3 s, n=1000, \( \eta = 10^{12} \text{s} \))
- 1 Km detector (L=500m, T=10 s, n=5000, \( \eta = 10^{12} \text{s} \))

Frequency (Hz)
Example: IMBH $10^3 - 10^3 M_{\text{sol}}$

$3 \text{ Gpc, } 10^3 - 10^3 M_\odot$

$\sqrt{\text{Power Spectral Density / Hz}^{-1}}$

$10^{-22}$ to $10^{-18}$

Frequency / Hz

$10^{-2}$ to $10^4$

GW150914

Compact binary inspirals

GW150914

AdV

aLIGO

ET
Supernovae Ia and sensitivity

• Possibly visible within Milky Way, but infrequent (1/100 yr)
What about Newtonian noise?

- Potential **show-stopper**
- Cancellation *possible* with additional information from seismometers and microphones [to reject seismic and infrasound noise respectively]
- Require high sensitivity [SNR=O(10^3) at micro-seismic peak]
- Getting below 10^{-20} at 10^{-1} Hz is *plausible*.
- 10 mHz is a hard limit

“Internal” NN cancelling schemes

- Use an array of Al gradiometers to sample spatial variations of NN and subtract

- Promising, but claimed rejection factors [O(10)] still insufficient to achieve required sensitivity

Chaibi et al, PRD 93, 021101(R) (2016)

R&D and dedicated facilities are required to test and demonstrate subtraction/cancellation schemes for Newtonian Noise
Large-scale atom interferometers

10 m fountain at Stanford

12 m fountain at Wuhan

Cavity mirror suspensions

Al sensors
Large-scale atom interferometer ⇒ Sardegna?
Possible experiments with the new apparatus
**EUROPEAN QUANTUM FLAGSHIP PROGRAM**

![European Commission logo]

**“Gravity Quantum Sensors”**

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<th>Country</th>
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*Guglielmo M. Tino* - La Thuile, 26/2/2018