GW detection by atom interferometry
Status and prospects

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GWADW2019 - Isola d’Elba
24 May 2019
Laser cooling: Optical molasses

\[ \nu_L, \nu \to \nu_L \]

Lab ref. frame

\[ \nu_L(1-v/c) \to \nu_L(1+v/c) \]

Atom ref. frame

Atomic Temperature: \( k_B T = Mv_{\text{rms}}^2 \)

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:
- Na: 240 \( \mu \)K, 2.4 \( \mu \)K
- Rb: 120 \( \mu \)K, 360 nK
- Cs: 120 \( \mu \)K, 200 nK
- Sr: 180 nK, 460 nK

Idea: T. W. Hänsch, A. Schawlow, 1975
Exp. demonstration: S. Chu et al., 1985
Atom interferometry

$$\lambda_{dB} = \frac{h}{M \nu}$$

de Broglie wavelength


Atom interferometry and gravity
• 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
(MISURA ACCURATA di G MEDIANTE INTERFEROMETRIA ATOMICA)
Precision measurement of the Newtonian gravitational constant using cold atoms

G. Rosi¹, F. Sorrentino¹, L. Cacciapuoti², M. Prevedelli³ & G. M. Tino¹

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 is 26 parts per million).

The atom interferometer is realized using light pulses to stimulate 87Rb atoms at the two-photon Raman transition between the hyperfine levels of the ground state. 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.

Relative uncertainty: 150 ppm

\( G = 6.67191(77)(62) \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2} \)
Ultracold Sr - Experiments in Firenze

• Optical clocks using visible intercombination lines


• New atomic sensors for fundamental physics tests


Microwave vs. optical clocks

Measure gravitational red shift in the lab

Fig. 3. Gravitational time dilation at the scale of daily life. (A) As one of the clocks is raised, its rate increases when compared to the clock rate at deeper gravitational potential. (B) The fractional difference in frequency between two Al* optical clocks at different heights. The Al-Mg clock was initially 17 cm lower in height than the Al-Be clock, and subsequently, starting at data point 14, elevated by 33 cm. The net relative shift due to the increase in height is measured to be $(4.1 \pm 1.6) \times 10^{-17}$. The vertical error bars represent statistical uncertainties (reduced $\chi^2 = 0.87$). Green lines and yellow shaded bands indicate, respectively, the averages and statistical uncertainties for the first 13 data points (blue symbols) and the remaining 5 data points (red symbols). Each data point represents about 8000 s of clock-comparison data.

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

\[ \nu = \frac{m g \lambda}{2 \hbar} \]

Scheme for the measurement of small distance forces

Objective: $\lambda = 1-10 \ \mu m$, $\alpha = 10^3-10^4$

F. Sorrentino, A. Alberti, G. Ferrari, V. V. Ivanov, N. Poli, M. Schioppo, and G. M. Tino,
*Quantum sensor for atom-surface interactions below 10 $\mu m$, Phys. Rev. A 79, 013409 (2009)*
Test of the EP for 0-spin and half-integer-spin atoms: Search for spin-gravity coupling effects

Einstein Equivalence Principle
→ Universality of the Free Fall

The trajectory of a freely falling “test” body is independent of its internal structure and composition

Test of the equivalence principle with two isotopes of strontium atom:

<table>
<thead>
<tr>
<th>$^{88}$Sr</th>
</tr>
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<tbody>
<tr>
<td>• Total spin = 0</td>
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<tr>
<td>• Boson</td>
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<table>
<thead>
<tr>
<th>$^{87}$Sr</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Total spin $\equiv$ nuclear spin $I = 9/2$</td>
</tr>
<tr>
<td>• Fermion</td>
</tr>
</tbody>
</table>

Comparison of the acceleration of $^{88}$Sr and $^{87}$Sr under the effect of gravity by measuring the Bloch frequencies in a vertical optical lattice

Search for EP violations due to spin-gravity coupling effects

Atom interferometry with the Sr optical clock transition

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

Liang Hu, Nicola Poli, Leonardo Salvi, Guglielmo M. Tino,
Atom interferometry with the Sr optical clock transition,
**Squeezing on momentum states for atom interferometry**

Goal: production of squeezed states of the atomic center-of-mass motion that can be injected into an atom interferometer.

Proposed method: dispersive probing in a ring resonator on a narrow transition for a collective measurement of the relative population of two momentum states.

Frequency splitting from Doppler effect

\[ \delta \omega = 2\pi n \times 28.6 \text{ kHz} \]

Condition for dispersive regime:

\[ \delta \omega \gg \Gamma \]

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Gravitational waves detection with atom interferometry

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

Build the
The sensitivity (2)

\[ h = L \frac{\gamma}{\sqrt{\Omega C}} \]

- \( v_s = 10^6 \text{ m/s} \), \( N = 10^6 \text{ atoms(H)} \)
- \( T = 10^{-3} \text{ s} \), \( L = 10^3 \text{ m} \), \( v_f = 10 \text{ m/s} \)

- \( v_f = 10^{-3} \text{ m/s} \), \( L = 10^{-1} \text{ m} \)
- \( T = 10^{-1} \text{ s} \)

- \( v_s = 10 \text{ m/s} \), \( v_f = 5 \text{ m/s} \), \( L = 50 \text{ m} \)
- \( N = 10^8 \text{ atoms(Cs)} \)

• 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 23-02-2009 to 24-02-2009
Deadline: 15-01-2009

Note: 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 in 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 of atom interferometry and gravitational wave detection. It will offer a forum for exchange of ideas and future directions of research in the field of gravitational wave detection.
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
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 $^{87}$Sr, Ca, Yb, Hg, etc.).
- Atoms act as clocks, measuring the light travel time across the baseline.
- GWs modulate the laser ranging distance.

Gravitational wave detection with clocks

\[
\sigma(\tau) = \left. \frac{\delta v}{v_0} \right|_{\tau} = \frac{\sqrt{\Delta_A}}{v_0 \sqrt{2\pi \tau N}}
\]

from J. Ye

Proposal title

SPACE ATOMIC GRAVITY EXPLORER

Acronym

SAGE

Lead Proposer
Prof. Guglielmo M. Tino

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 velocities
• Use clocks and links between satellites for optical VLBI in Space

September 13, 2016
SAGE: GW detection
(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 $\rightarrow \Delta v=20$ $\mu$Hz
- Rabi frequency $\Omega \sim 1$kHz

Atom interferometry with the Sr optical clock transition

Liang Hu, Nicola Poli, Leonardo Salvi, Guglielmo M. Tino,
Atom interferometry with the Sr optical clock transition,
Development of a strontium optical lattice clock for the SOC mission on the ISS

SAGE: SPACE ATOMIC GRAVITY EXPLORER
Strontium Atomic Interferometers and Clocks in Space for Fundamental Physics and Applications

Firenze, 2011
From table-top experiments to large-scale detectors
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, \( \eta = 10^5 / s \))
- **MAGIA upgraded** (L=0.5m, T=0.3 s, n=10, \( \eta = 10^8 / s \))
- 10 m demonstrator (L=5m, T=1 s, n=100, \( \eta = 10^{12} / s \))
- 100 m detector (L=50m, T=3 s, n=1000, \( \eta = 10^{12} / s \))
- 1 Km detector (L=500m, T=10 s, n=5000, \( \eta = 10^{12} / s \))
Example: IMBH $10^3 - 10^3 \, M_{\text{sol}}$

Compact binary inspirals

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

$\sqrt{\text{Power Spectral Density} / \text{Hz}^2}$

$10^{-2}$ $10^0$ $10^2$ $10^4$

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

GW150914

AdV

aLIGO

ET
Large-scale atom interferometers

10 m fountain at Stanford

12 m fountain at Wuhan

Cavity mirror suspensions

Al sensors
MIGA Project

A new large instrument combining matter-wave and laser interferometry

- **Gravitational wave physics**
- **Demonstrator for future sub-Hz ground based GW detectors**
- **Geoscience**
  - Gravity sensitivity of $10^{-10} \text{g}/\text{Sqrt(Hz)}$ @ 2Hz
  - Gradient sensitivity of $10^{-13} \text{s}^{-2}/\text{Sqrt(Hz)}$ @ 2Hz: geology, hydrogeology...

A Large research infrastructure hosted in a low noise laboratory

- Two 200 m horizontal optical cavity coupled with 3 AI
- Possible evolutions towards 2D or 3D instrument on site

- from P. Bouyer, 2018
MIGA Project - Status

First 150 meters drilled


From P. Bouyer, May 2019

http://miga-project.org/
MAGIS Collaboration

Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS-100)

Phil Adamson¹, Swapan Chattopadhyay¹,², Jonathon Coleman⁵, Peter Graham³, Steve Geer¹, Roni Harnik¹, Steve Hahn¹, Jason Hogan⁴,⁵, Mark Kasevich⁵, Tim Kovachy⁶, Jeremiah Mitchell², Rob Plunkett¹, Surjeet Rajendran⁴, Linda Valerio¹ and Arvydas Vasonis¹

¹Fermi National Accelerator Laboratory; Batavia, Illinois 60510, USA
²Northern Illinois University; DeKalb, Illinois 60115, USA
³Stanford University; Stanford, California 94305, USA
⁴University of California at Berkeley; Berkeley, CA 94720, USA
⁵University of Liverpool; Merseyside, L69 7ZE, UK
⁶Northwestern University; Evanston, Illinois, USA

Part of the proposed Fermilab Quantum Initiative:

from J. Hogan
Matter wave Atomic Gradiometer Interferometric Sensor

- 100-meter baseline atom interferometry in existing shaft at Fermilab
- Intermediate step to full-scale (km) detector for gravitational waves
- Clock atom sources (Sr) at three positions to realize a gradiometer
- Probes for ultralight scalar dark matter beyond current limits (Hz range)
- Extreme quantum superposition states: >meter wavepacket separation, up to 9 seconds duration
Received funding from the Gordon and Betty Moore Foundation for the project, beginning in January 2019.

Received Stage I approval from the Fermilab directorate to proceed with the experiment. Beginning preliminary designs.

The goal is to begin commissioning the detector in about two years.

(From J. Hogan, May 2019)
An underground facility for GR tests using large scale atomic interferometers, gyros and clocks

- ZAIGA-GW (Gravitation Wave detection)
- ZAIGA-EP (Equivalence Principle test)
- ZAIGA-CR (Clock Redshift measurement)
- ZAIGA-RM (Rotation Measurement)
- ZAIGA-GG (Geological and Geophysical measurement)

$H \sim 300 \text{ m}$

$L \sim 1/3/10 \text{ km}$

from M. S. Zhan

arXiv:1903.09288v2, accepted for publication in Int.J.Mod.Phys.B
Zhaoshan (沼山): a mountain near Wuhan, China
Completed site exploration with tunnel excavation starting in 2019.

The first phase of ZAIGA should be complete by the end of 2020. 300 m vertical tunnel to test the weak equivalence principle of GR.

If the project is fully funded, it could be operational by 2025.

(From Mingsheng Zhan, May 2019)
AION Project: Core Team

- **Birmingham**
  - Kai Bongs*
  - M. Holynski*
  - Y. Singh*

- **Cambridge**
  - V. Gibson**
  - U. Schneider*

- **Imperial College London**
  - O. Buchmueller** [co-coord.]
  - M. Tarbutt*
  - B. Sauer*

- **Kings College London**
  - J. Ellis*

- **Liverpool**
  - T. Bowcock**
  - J. Coleman** [co-coord.]

- **National Physical Lab.**
  - W. Bowden*
  - P. Gill*
  - R. Hobson*

- **Oxford**
  - E. Bentine*
  - C. Foot*
  - J. March-Russell**
  - I. Shipsey**
  - I. Willmut**

- **Rutherford Appleton Lab.**
  - P. Majewski**
  - T. Valenzuela**

- **Main UK funding source:**
  *EPSRC; **STFC

from O. Buchmueller
What is AION (in a nutshell)?

• The proposal is to construct and operate a next generation Atomic Interferometric Observatory and Network (AION) in the UK that will enable the exploration of properties of dark matter as well as searches for new fundamental interactions.

• It will provide a pathway for detecting gravitational waves from the very early universe in the, as yet mostly unexplored, mid-frequency band, ranging from several milliHertz to a few Hertz.

• The proposed project spans several science areas ranging fundamental particle physics over astrophysics to cosmology and, thus, connects these communities.

• Following the “Big Ideas” call, the project was selected by PAAP and STFC as a high priority for the community. It was provisionally classified as a medium scale project.

• AION is also a Work Package of the QSFP proposal
AION – A Staged Programme**

AION-10: Stage 1 [year 1 to 3]
- 1 & 10 m Interferometers & Site Development for 100m Baseline

AION-100: Stage 2 [year 3 to 6]
- 100m Construction & Commissioning

AION-KM: Stage 3 [ > year 6 ]
- Operating AION-100 and planning for 1 km & Beyond

AION-SPACE: Stage 4 [ after AION-KM ]
- Space based version

**outlined in Big Ideas proposal

from O. Buchmueller
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
Large-scale atom interferometer ⇒ Sardegna?

Carbonia-Iglesias
ARIA/Darkside Lab

Sos Enattos
SAR-GRAV Lab?
The end
The Beginning
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=$\mathcal{O}(10^3)$ at micro-seismic peak]
- Getting below $10^{-20}$ at $10^{-1}$ Hz is plausible.
- $10$ mHz is a hard limit

“Internal” NN cancelling schemes

R&D and dedicated facilities are required to test and demonstrate subtraction/ cancellation schemes for Newtonian Noise

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

- Use an array of AI gradiometers to sample spatial variations of NN and subtract
- Promising, but claimed rejection factors [ O(10) ] still insufficient to achieve required sensitivity