An Experiment for Direct Detection of Dark Energy

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Ultra Cold Atom Interferometry

Developing Next Generation Gravity Sensors & Gyroscopes for Direct Dark Energy Detection and Fundamental Physics

Work in Collaboration with Martin Perl (Nobel Laureate, visiting professor @ U. Of Liverpool)

Particle Physics Proto-Collaboration:
Introduction

• Motivate a parameter space search for direct detection of the dark contents of the vacuum
• Introduce the concept of atom interferometry
• Construction of the prototype at Liverpool
• Future Upgrade Scenarios

M. Perl et al, A terrestrial search for dark contents of the vacuum, such as dark energy, using atom interferometry
arXiv:1101.5626
Nature of Dark Energy

- Cosmological observations indicate 68% of the universe is dark energy.
- Present theory offers no fundamental understanding of the nature of dark energy.
- Dark energy has a small but non-zero density $1.67 \times 10^{-27} \text{ kg m}^{-3}$. Is this measureable on a terrestrial scale?

Planck Results
arXiv:1303.5062
Conditions of Detection

An experiment to investigate the effect of Gravity on quantum systems.

Allows for the **Direct Detection** of Dark Energy if:

- Vacuum fluctuations are spatially inhomogeneous on the lab scale.
- The vacuum interacts with atoms in a non gravitational way.
Theory with Caveats:

Distance Scale of meters

Distance Scale of universe

Dark Energy Potential

$V_N$
Experimental Concept

- Two spatially separated interferometers in the same noise conditions.
- System is designed to minimize/eliminate the effects of gravity and many other sources of noise.
Nature of Measurement

• not recording $\Delta \phi$ which will average to zero,
• measure instead the root mean square $\Delta \phi$ rms.
• can then determine the dark energy equivalent acceleration, $g_{DE}$.
• We expect to be able to detect the dark energy equivalent acceleration, $g_{DE}$ with a precision of $\rightarrow 10^{-15}$ m/s$^2$.

• sampling rate - order of Hertz.
• Hence signal is a noise like.
Analogy with Light Interferometer

- Split light into two beams.
- Beams travels two different paths.
- Recombine the beams into one.
- Measure the phase difference between the two paths.
- Phase difference related to change in path.
Atom Interferometer Overview

- Magneto optical trap (MOT) sources cold atom cloud.
- Atoms form optical molasses and dropped.
- Selects atoms in magnetically insensitive state and a narrower range of velocities.
- Interferometry splits the atom cloud, allow phase to accumulate and recombine cloud.
- Detect ratio of atoms in different states at bottom – related to phase difference.
Interferometry sequence

1. 3D Magneto-Optical Trap, then state selection
2. Free fall
3. Raman π/2 pulse (Splitting)
4. Interrogation time T
5. Raman π pulse (Mirror)
6. Interrogation time T
7. Raman π/2 pulse (Recombination)
8. Detection
Phase Accumulation

- Three components contribute to atoms phase.
- Phase is accumulated in free fall.

Systematics
- Laser phase is printed on the atoms with ‘beamsplitters’ or ‘mirrors’
- A phase is associated with the atoms not quite recombining for detection.

\[ \Delta \phi_{total} = \Delta \phi_{prop} + \Delta \phi_{laser} + \Delta \phi_{sep} \]
Atom Interferometer at Liverpool

Ultra-cold atom source.

State selection

Light pulse interferometry region

Detection.
3D Atom Trap - Interferometer Source

Vacuum @ \( > 10.4 \times 10^{-10} \) mbar
Frequency Control System

- Many different frequencies required for the atom interferometer.
- Optical circuit generates all required frequencies from extended cavity diode lasers (ECDL) and acousto-optical modulators (AOM).
Frequency generation and detection sequence components currently being commissioned and optimised
Improving Sensitivity

- depends upon having large phase shift $\phi$: 
  $\phi = \text{constant}\ (gT^2)$

- $T$ is time of flight for the atom cloud

- Prototype under construction height $\sim 1\ m$ and $\phi \sim 107\ \text{radians}$

- $T^2$ is proportional to $h$,

- $h = 10\ m$, approx $10\ x$ improvement in $\phi$,

- Daresbury tower $\sim 100\ m$

- benefits of exploiting this structure are obvious.
Possible Site Location

- Highly stable bedrock as foundations of Tower structure
- 8 m high previous Medium Energy Ion Source (MEIS) room?
The Future?

- 10 m Atom Interferometers are being developed worldwide
- Daresbury Tower is ideal for this

Stanford, USA

Center for Cold Atom Physics, Chinese Academy of Sciences, Wuhan
Roadmap

• Key Milestones Identified
• Manufacture & Cost Identified for Core Components
• Collaboration gaining critical Mass
Summary

- An Experiment to Investigate the Dark Content of the Vacuum
- Possible signature for Direct Detection of Dark Energy
- Investigating a new area of experiment
  - Unexplored phase space
- Rich area of Physics Measurements
- A possible future use of the tower

- **New Collaborators are Welcome**
Backup slides
State of Art: AI Gravimeters + Gradiometers

Stanford Gravimeter (non-mobile)
Achieved Accuracy: $4 \cdot 10^{-9}$ g ( ?)

Paris Gravimeter ("mobile")
Achieved Accuracy: $4 \cdot 10^{-9}$ g

Florenz INFN Gravity Gradiometer MAGIA
Measurement of the gravitational constant $G$
Targeted Accuracy: $\Delta G/G \ 1 \cdot 10^{-4}$

Kasevich Gravimeter (mobile)
Bias Stability: $< 10^{-10}$ g

Berlin Gravimeter GAIN
(mobile, under construction)
Targeted Accuracy: $5 \cdot 10^{-10}$ g
Measuring gravity as a Benchmark

- Laser frequencies need chirping to account for the Doppler shift of atoms.
- Varying chirping scans the interferometer fringes, which can be fit to obtain value of g.

A. Peters et al

doi:10.1088/0026-1394/38/1/4
Experimental Configuration

To cancel systematic effects:

- Incorporate the two interferometers in one vacuum envelope,
  - reduce problems from common mode noises such as vibrations.
  - drop sources for simplicity.
- Sources are staggered vertically,
  - total phase change for each atom is measured during the same velocity period.