Atom Interferometry Systematics and Challenges with AION-100

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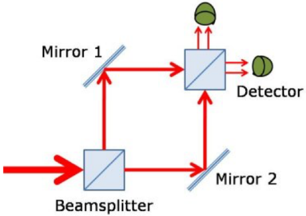
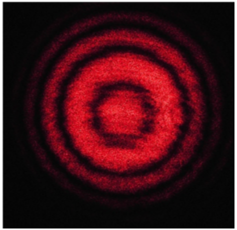
26 October 2021

Outline

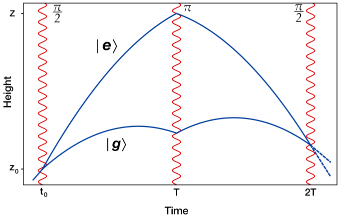
Laser interference

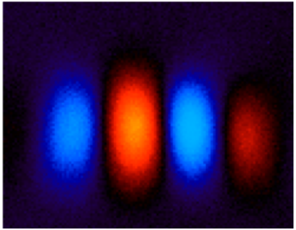


http://www.cobolt.se/interferometry.html

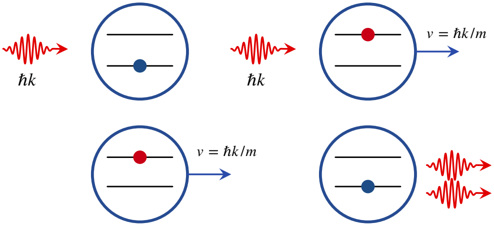


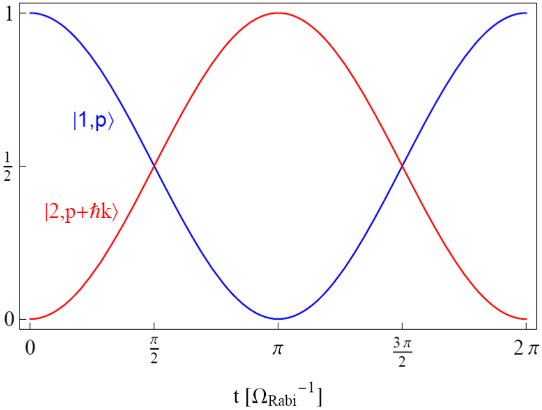
Matter-wave interference



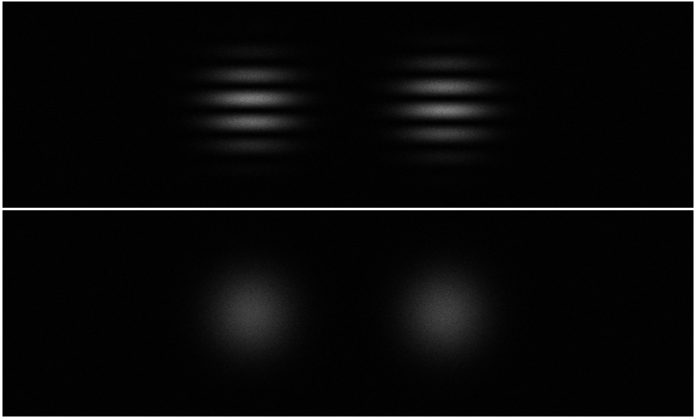


- Atom optics implemented through stimulated absorption/emisison
- Raman scattering or Bragg scattering modes
- Two photon and single photon transitions





Simulated atom cloud interference pattern pixelated images. Images, going from the top to the bottom, are of the xz projection where z runs horizontally, yz projection with z running horizontally, and xy projection from top down view.



Atom Interferometry Phase

$$\Delta\phi = \Delta\phi_{\text{laser}} + \Delta\phi_{\text{propagation}} + \Delta\phi_{\text{separation}}$$

$$\Delta\phi_{\text{laser}} = \sum_{j}^{\text{upper}} \pm\phi_L(t_j, \mathbf{x}_u(t_j)) - \sum_{j}^{\text{lower}} \pm\phi_L(t_j, \mathbf{x}_l(t_j))$$

$$\Delta\phi_{\text{propagation}} = \sum_{\text{upper}} \left(\int_{t_i}^{t_f} (L_c - E_i)\,\mathrm{d}t \right) - \sum_{\text{lower}} \left(\int_{t_i}^{t_f} (L_c - E_i)\,\mathrm{d}t \right)$$

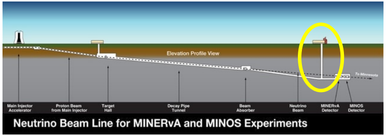
$$\Delta\phi_{\text{separation}} = \langle \mathbf{p} \rangle \cdot \Delta\mathbf{x}$$

$$\phi_L(t, \mathbf{x}(t)) = \mathbf{k}_{\text{eff}} \cdot \mathbf{x}(t) - \omega t + \delta$$

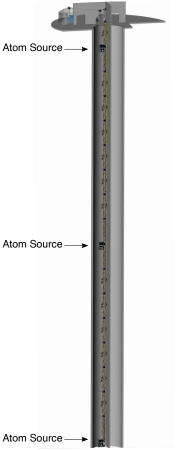
MAGIS-100 uses 100 m baseline with three atom sources

Science Goals

- Dark matter detection
- Gravitational wave detector prototype
- Extreme macroscopic quantum mechanics



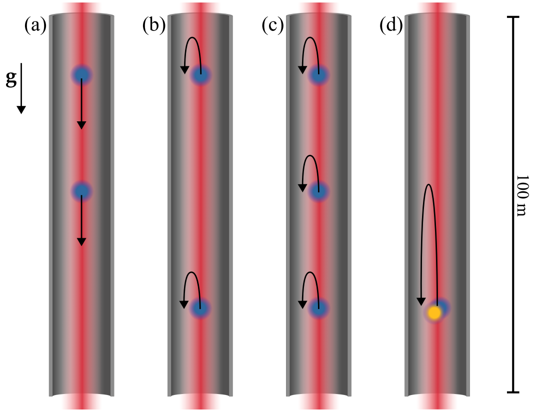
[Abe, Mahiro, et al. QST (2021). arXiv:2104.02835v1]



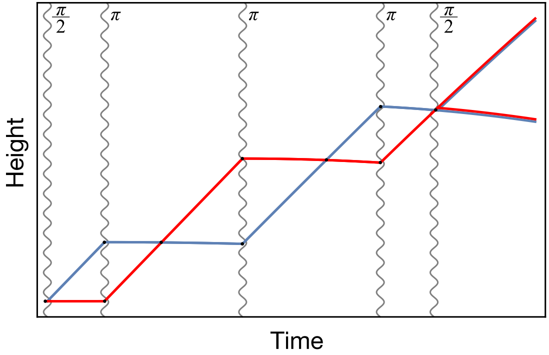
- Multi-stage program with AION-10 → AION-100 → AION-km
- Will begin with 2 strontium atom sources
- Looking for ultra light dark matter signals
- AION-10 could provide early network data in conjunction with MAGIS prototype tower and MAGIS-100

[Badurina, et al. 2020. arXiv:1911.11755v3]

Atom Interferometry Advancements



Multiple configurations

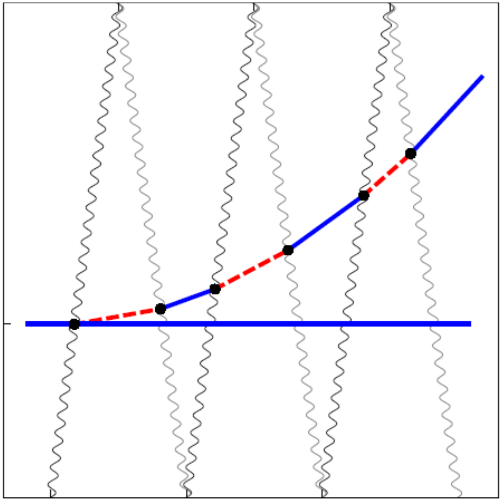


Large momentum transfer (LMT) and multi-loop atom interferometry

Large Momentum Transfer (LMT)

- Multiple laser pulses to accelerate one of the atom interferometer arms
- Coherently enhance differential phase measurement scales with n the number of LMT pulses

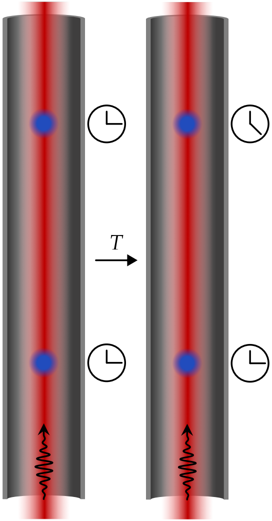
$$\Delta\phi \sim 2n\omega_A(L)$$



Graham, et al. PRL (2013)

- Clocks are started simultaneously ticking with frequency ω_A
- Fluctuation of laser alters clock measurement of time $T \rightarrow T + \Delta T$

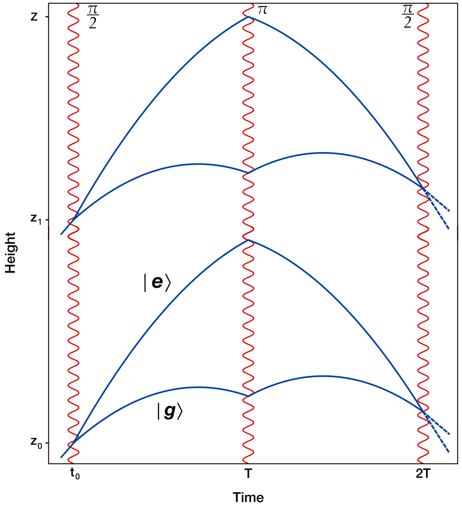
Initial States	$\frac{1}{\sqrt{2}}\lvert g\rangle + \frac{1}{\sqrt{2}}\lvert e\rangle$
Lower Source	$\frac{1}{\sqrt{2}}\lvert g\rangle + \frac{1}{\sqrt{2}}\lvert e\rangle\, e^{-i\omega_a T}$
Upper Source	$\frac{1}{\sqrt{2}}\lvert g\rangle + \frac{1}{\sqrt{2}}\lvert e\rangle\, e^{-i\omega_a (T+\Delta T)}$



Gradiometer

- Simultaneous interferometer interference measurement
- Common laser allows common mode noise suppression

$$\frac{1}{\sqrt{2}}\left|g_0\right\rangle+\frac{1}{\sqrt{2}}\left|e_0\right\rangle e^{i\phi_L}$$
$$\frac{1}{\sqrt{2}}\left|g_1\right\rangle+\frac{1}{\sqrt{2}}\left|e_1\right\rangle e^{i\phi_L}$$



Detector Subsystems and Systematics

Main subsystems to consider for systematics and noise sources

- Laser system
- Atom Sources
- Detector environment
- Detection and readout

Systematics

- Temperature fluctuations and gradients
- Magnetic field fluctuations
- Seismic fluctuations and vibrations
- Gravity Gradient Noise
- EM noise

Understanding Systematics and Noise

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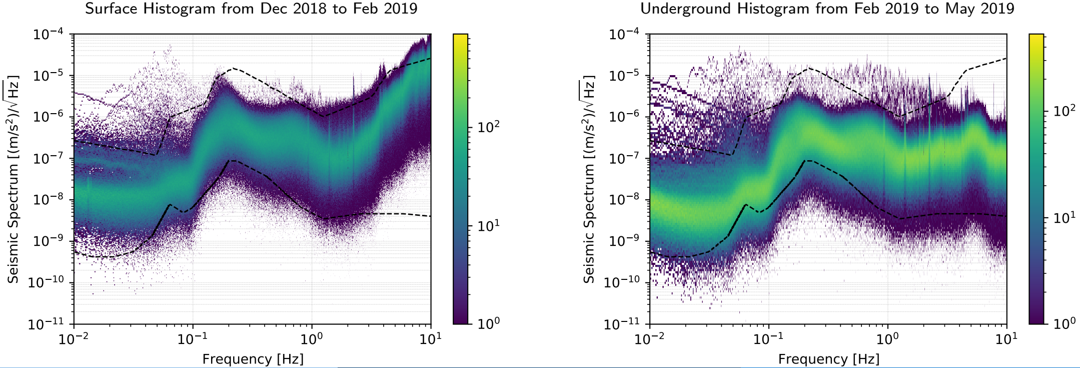
- Crucial for maximizing detector sensitivity
- Plays important R&D role for long baseline atom interferometers
- Goal is to understand leading order systematics and devise methods for mitigating them
- Interesting leading order effects sourced by environment: seismic vibration, rotations and gravity gradients, gravity gradient noise (GGN), magnetic fields, blackbody radiation shifts, background gas index of refraction
- Full list can be found in [Abe, Mahiro, et al. QST (2021). arXiv:2104.02835v1]

Ambient Seismic Noise

$$PSD\{x(t)\} = \frac{2(\Delta t)^2}{T}|x(\omega)|^2,$$

$$x(\omega) = DFT\{x(t)\} = \sum_{t=0}^{N-1} x(t)e^{2\pi it/N}.$$



Vibrational Noise Estimates

- Vibration couples to lasers and initial atom ensemble kinematics

$$\delta\phi_{\text{vibration}} \sim \left(10^{-9}\,\text{rad}/\sqrt{\text{Hz}}\right)\left(\frac{n}{100}\right)\left(\frac{\Delta v}{10\,\mu\text{m/s}}\right)\left(\frac{T}{1\,\text{s}}\right)\left(\frac{\delta a}{10^{-4}\,\text{m/s}^2/\sqrt{\text{Hz}}}\right)$$

$$\delta\phi_{\text{RGGV}} \sim \left(2\times 10^{-6}\,\text{rad}/\sqrt{\text{Hz}}\right)\left(\frac{n}{100}\right)\left(\frac{\Delta v_x}{1\,\mu\text{m/s}/\sqrt{\text{Hz}}}\right)\left(\frac{T}{1\,\text{s}}\right)$$

Can be mitigated by vibrational isolation on laser tables, large stable pedestal mounts for the laser transport system

Gravity Gradient Noise (GGN)

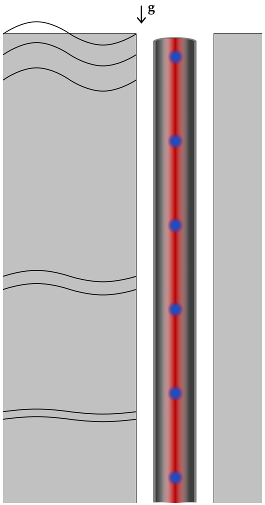
- Gravity gradient noise is second order effect where seismic surface waves (Rayleigh waves) couple to gravitational potential field
- Perturbations in gravitational potential field lead to perturbations in test mass acceleration
- Atom trajectories are perturbed under free fall and pickup a phase shift leading to a spurious strain of

$$\delta h_{\rm ggn} = \frac{\pi G \gamma_\nu \rho_0}{2LT\omega_{ggn}^3} \langle \delta\xi_z \rangle \left(e^{-\sqrt{2}L\omega_{ggn}/c_R} - 1 \right) \sin(\omega_{ggn} T) \cos(\phi_{ggn})$$

$$\delta h_{\rm ggn} \sim \left(10^{-19}/\sqrt{\rm Hz}\right) \left(\frac{100\,{\rm m}}{L}\right) \left(\frac{1.5\,{\rm s}}{T}\right) \left(\frac{1\,{\rm Hz}}{\omega_{ggn}}\right)^3 \left(\frac{\delta\xi_z}{1\,\mu{\rm m}}\right) \left(\frac{300\,{\rm m/s}}{c_R}\right)$$

GGN Suppression and Mitigation

- String-of-pearls characterization
- Residual linear strain noise interferes with GW and DM measurements
- Suppression factor defined by ratio of linear fitting and simulated gradiometer phase difference along the baseline
- Correlated seismometer array at the surface and *in situ* calibration data



GGN Modeling

- Modeled gravity gradient noise (GGN)
  - Test mass acceleration perturbation caused by density perturbations of ground and atmosphere
  - Important systematic that limits MAGIS-100 maximum sensitivity

Short wavelength approximation:

$$h_{GGN} = \frac{G\rho_0}{2\pi f^2 L} \langle \xi_z \rangle$$

Long wavelength approximation:

$$h_{GGN} = \frac{G\rho_0}{f c_R} \langle \xi_z \rangle$$

Using simple model convert between measured seismic displacement amplitude spectra into inferred GGN strain

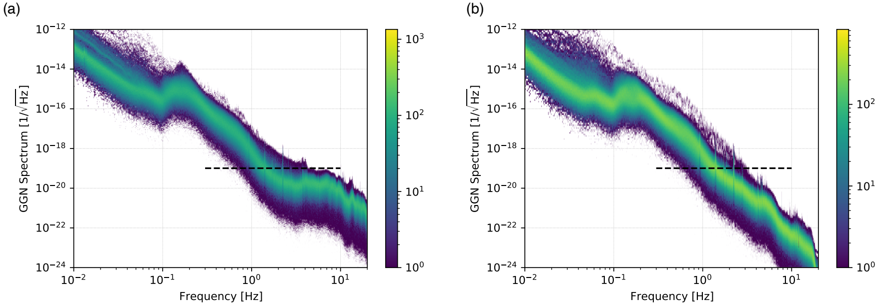


Figure 1: Inferred GGN strain spectrum (a) from surface measurements, (b) from underground measurements. Black dashed line is strain sensitivity after advancements.

Temperature Systematics

Estimates for blackbody radiation shifts and background gas index of refraction fluctuations

$$-2.3\,\mathrm{Hz}\left(\frac{T_{sys}}{300\,\mathrm{K}}\right)^4$$

Leads to $1 \times 10^{-6}\,\mathrm{rad}/\sqrt{\mathrm{Hz}}$ for fluctuation $\sim 1\,\mathrm{K}$ over 1 hour period

$$\delta h_{index} = \delta\eta \sim \left(4 \times 10^{-26}\,/\sqrt{\mathrm{Hz}}\right)\left(\frac{P}{10^{-11}\,\mathrm{Torr}}\right)\left(\frac{300\,\mathrm{K}}{T_{sys}}\right)\left(\frac{\delta T_{sys}}{1\,\mathrm{K}}\right)$$

$$\delta h_{index} = \delta\eta \sim \left(4 \times 10^{-21}\,/\sqrt{\mathrm{Hz}}\right)\left(\frac{P}{10^{-11}\,\mathrm{Torr}}\right)\left(\frac{300\,\mathrm{K}}{T_{sys}}\right)\left(\frac{\delta P/P}{0.001\,/\sqrt{\mathrm{Hz}}}\right)$$

Magnetic Field Fluctuations

- Sr clock energy levels shift under magnetic fields
- Time-varying fields cause frequency shifts mimicking GW or ULDM signals
- Employing magnetic shielding and co-magnetometer linear suppression using gradiometer measurement with opposite magnetic field response
- Estimate of residual background for bias field B_0

$$\delta\phi_{mag} \sim \left(1 \times 10^{-3}\,\mathrm{rad}/\sqrt{\mathrm{Hz}}\right)\left(\frac{B_0}{1\,\mathrm{G}}\right)\left(\frac{\delta B}{1\,\mathrm{mG}/\sqrt{\mathrm{Hz}}}\right)\left(\frac{T}{1\,\mathrm{s}}\right)$$

Engineering Systematics

- Vibration effects on truss and support systems
- Temperature effects on vacuum pipe expansion
- Requires mitigation such as enclosures and shielding

Summary

- Leading systematics are being studied and analyzed for MAGIS-100
- AION and MAGIS-100 design depend on understanding site specific temperature and vibration environment
- Mitigation strategies ensure crucial precision of when operation begins and are applicable to future long baseline atom interferometers

MAGIS-100 Collaboration

Stanford University, Fermilab, Northwestern University, University of Liverpool, Northern Illinois University, Johns Hopkins University, University of Cambridge, University of Oxford

AION Collaboration

Imperial College London, King's College London, University of Birmingham, University of Cambridge, University of Oxford, University of Liverpool, Science & Technology Facilities Council

Support from the Kavli Foundation