A search for Non-Newtonian Gravity with Ultracold atoms

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Background

Various string theories predict the existence of non-Newtonian gravitational interaction due to the presence of extra dimensions. Using ultra cold atoms in a well confined potential, one can put constraints on these theories at length scales of less than 10μm. This is done by carefully probing the atom-surface interaction, and then subtracting out all electromagnetic potentials (example: Casimir-Polder potential, and patch potentials) so as to detect these minute gravitational signals.

Gravity on the micron scale

Non Newtonian gravitational interaction between two masses m_1 and m_2 are represented by Yukawa-like potentials:

$$V_G(r) = -G\frac{m_1 m_2}{r}\left[1+\alpha\exp(-r/\lambda)\right]$$

G is the Newtonian gravitational constant

α parameterize the strength of non-Newtonian gravity

λ parameterize the range of non-Newtonian gravity

For an atom of mass m close to a flat surface density ρ, the Yukawa gravitational contribution evaluates to

$$V_G(z) = -2\pi\alpha\lambda^2 G\rho m\, e^{-z/\lambda}$$

Casimir-Polder potential

The dominant electromagnetic potential near the surface is the Casimir potential, and near a perfect conductor, it can be represented as:

$$V_{CP}(r) = -\frac{C_4}{r^4},\ C_4 = \frac{3\hbar c\alpha_{DC}}{32\pi^2\varepsilon_0}$$

α_{DC} is the static polarizability of the atom.

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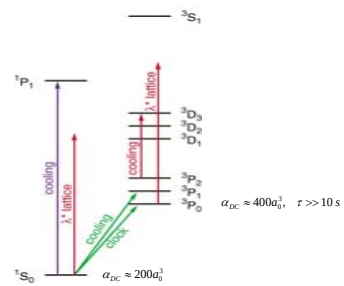
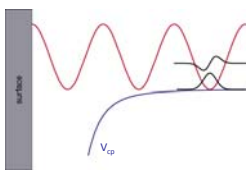
Ultracold Ytterbium atoms can be used to probe these very weak potentials



- Can choose magic wavelength λ* such that the AC stark shift of $^1S_0$ and $^3P_0$ are identical
- Narrow line laser cooling to T~10 μK
- $^1S_0$ and $^3P_0$ states have different static polarizabilities, which mean they will experience different Casimir-Polder shifts.
- Ratio of Casimir-Polder shifts is given by ratio of their polarizabilities.
- $^1S_0$ and $^3P_0$ have zero magnetic moment (J=0), therefore only electric forces need to be considered here

Probing Atom-Surface interaction



- Cool atoms to ground state of optical lattice.
- Measure frequency difference between vibration levels.
- Casimir-Polder potential perturbs frequency splitting by $\Delta\nu$ ~ 10 Hz @ 1 µm.

$$\frac{V_{CP}(^3P_0)+V_G}{V_{CP}(^1S_0)+V_G} = \frac{\alpha_{DC}(^3P_0)}{\alpha_{DC}(^1S_0)}\left[1-\frac{\Delta\alpha_{DC}}{\alpha_{DC}}\frac{V_G}{V_{CP}}\right]$$

$$\Rightarrow V_G \approx \frac{\alpha_{DC}(^3P_0)}{\alpha_{DC}(^3P_0)-\alpha_{DC}(^1S_0)}\delta V_{CP} \qquad \Delta\omega_G = -\pi\alpha G\rho e^{-z/\lambda}/\omega$$

Detectable gravity signal — experimental measurement uncertainty — Shift in trap frequency due to atom surface interaction

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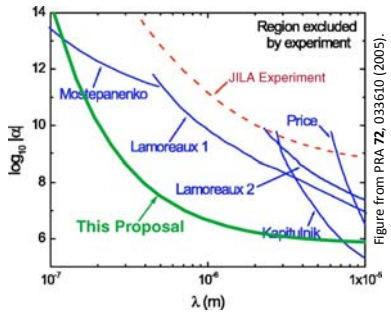
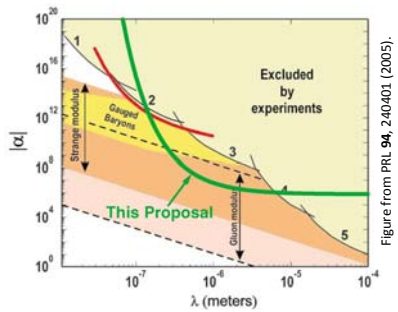
Expected experimental limits



- Casimir-Polder potentials cancel at the $\Delta\omega$= 10^{-3} level.
- Casimir-Polder theory accurate at the $\Delta\omega$=10^{-1} level.

Theoretical predictions



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