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 10⁻²⁴ m. 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:

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

\( G \) is the Newtonian gravitational constant
\( \alpha \) parameterize the strength of non-Newtonian gravity
\( \lambda \) parameterize the range of non-Newtonian gravity

For an atom of mass \( m \) close to a flat surface density \( \rho \), 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:

\[
V_{CP}(r) = -C \frac{1}{r^2}, \quad C_4 = \frac{3hc\alpha_{DC}}{32\pi^2\epsilon_0}
\]

\( \alpha_{DC} \) is the static polarizability of the atom.

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

- Can choose magic wavelength \( \lambda^* \) such that the AC stark shift of \( ^1S_0 \) and \( ^3P_0 \) are identical
- Narrow line laser cooling to \( T \approx 10^{-10} \mu\text{K} \)
- \( ^1S_0 \) 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 \( \Delta \nu \approx 10 \text{ Hz} @ 1 \mu\text{m} \)

Expected experimental limits

- Casimir-Polder potentials cancel at the \( \Delta \nu = 10^{-10} \text{ level} \).
- Casimir-Polder theory accurate at the \( \Delta \nu = 10^{-10} \text{ level} \).

Theoretical predictions

References: