Towards Quantum Gravity Measurement by Cold Atoms

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Quantum Fields, Gravity & Information
1. Quantum Gravity observation difficulties
2. Probing Spacetime with cold atoms
3. Quantum mechanical and Thomas-Fermi approach
4. Mechanism of Observation (Experiment)
Quantum Gravity Observation Difficulties

Paradoxical but Possible

Impossibility

“Relativity” and “Ascending & Descending”
by M.C. Escher
Quantum Gravity Observation Difficulties

\[ R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu} \]

\[ i\hbar \frac{\partial}{\partial t} \Psi(r, t) = (-\frac{\hbar^2}{2m} \nabla^2 + V(r, t))\Psi(r, t) \]

10\(^{-33}\) cm

10\(^{19}\) GeV

10\(^{-43}\) s

14 \cdot 10^3 GeV
In 2011 Charles H.-T. Wang & Collaborators proposed probing Spacetime by cold atoms. The ideal is based on a seemingly “Lamb shift of cold atoms centre of mass” induced by gravitational Perturbation.

Indirect Observation of Spacetime fluctuation created by a binary star system

Electron energy
Level shifts

Proton oscillates due to vacuum fluctuations of EM field

Cold atoms or BEC

Lamb Shift of Hydrogen atom
Cold atoms

Laser with the same frequency as the atoms resonance frequency slow down atoms to temperature of microKelvin range, i.e. **COLD ATOMS**.

Evaporative cooling extract high kinetic energy atoms, and further lower the temperature to nanokelvin forming **BOSE EINSTEIN CONDENSATES**.
From FDT, quadruple radiation of a particle and damping reach thermal equilibrium with stochastic Gravitational wave background.

\[ \langle h_{ij} h_{ij} \rangle = \frac{32G}{\pi c^5} \int_0^\infty E_T(\omega) d\omega \]

Where \( E_T \) the Planck spectral density with \( T \to 0 \)

\[ E_T(\omega) = \frac{1}{2} \hbar \omega + \frac{\hbar \omega}{e^{\hbar \omega / kT} - 1} \]

**BEC** 2nd derivative of its 1st order standard deviation due to spacetime fluctuation

\[ \frac{d^2 \langle x^{(1)i}(t)^2 \rangle}{dt^2} = \frac{32}{9\pi} v^2 t_p^2 \Omega^2 \]

\[ \langle x^{(1)i}(t)^2 \rangle = \langle \Delta r^2 \rangle = \frac{16}{9\pi} t_p^2 \Omega^2 \ell^2 \]

\[ \Delta E \approx \frac{4 \times 10^{-23}}{\hbar \omega} \mathcal{N}^{-2} \mathcal{L}^2 \]

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Considering a 1D harmonic oscillator perturbed by a potential $V(x,t)$, the Hamiltonian is given as

$$\hat{H} = \hat{H}_0 + V(x,t)$$

Where $V(x,t) = mA(t)x$ and $A(t) = A_0 \sin(\Omega t)$

$$VV(x,t) = mA(t)|\n, t\rangle |i\rangle$$

With expected value of position of the particle as

$$\langle n | x | i \rangle = \sqrt{\frac{\hbar}{2m\omega}} \langle n | \hat{a} + \hat{a}^\dagger | i \rangle$$
Now the 1st order perturbation Coefficient of probability expressed as

\[ c_{ni}^{(1)}(t) = \frac{im}{\hbar} \langle n \mid x \mid i \rangle \tilde{A}_t (\omega_{ni}) \]

The mean power spectral density is

\[ S_t (\omega_{ni}) = \frac{1}{t} \left\langle \tilde{A}_t^*(\omega_{ni}) \tilde{A}_t (\omega_{ni}) \right\rangle \]

The Transition probability is found to be

\[ P_{ni} = \frac{m^2}{\hbar^2} \left| \langle n \mid x \mid i \rangle \right|^2 S(\omega_{ni}) t \]

To calculate the total power absorbed by the particle Power spectral density can be given as

\[ S(\omega) = \frac{\pi A_0^2}{2} [\delta(\omega - \Omega) + \delta(\omega + \Omega)] \]

\[ P = \frac{\pi m A_0^2}{4} \delta(\omega - \Omega) \]

\[ \langle P \rangle = \frac{\pi ma^2 \Omega^3}{4} \]
Using a Rb87 BEC the GPE is given

\[ i\hbar \frac{\partial \psi(X,t)}{\partial t} = \left( -\frac{\hbar^2}{2m} \nabla^2 + V(X,t) \right) \psi(X,t) + \frac{4\pi\hbar^2 a_s}{m} |\psi(X,t)|^2 \psi(X,t) \]

The total trap potential includes the Mechanical induced oscillation

\[ V(X,t) = mA(t)z + \sum_{x,y,z} \frac{1}{2} m_\alpha \omega_x^2 X^2 \]

Thomas-Fermi approximation is used when Kinetic term in GPE is less than interaction

\[ n_{TF} = \frac{\mu - V(x,t)}{g} \quad n \approx \frac{\mu}{g} \]

Constant ratio of 1 for small perturbation low 1Hz, 10^8, 1mm
The same treatment was given to high frequency, and amplitude. There were observed perturbations on the ratio due to the mechanically induced oscillation.

At 2KHz, $10^6$ TF approximation fails

Constant ratio of 1 for small perturbation low 1KHz, $10^3$, 1cm

Constant ratio of 1 for small perturbation low 1KHz, $10^6$, 1cm
**Figure 1.** (Colour online) Experiment setup, 1–trap, 2–quarter wave plate, 3–fiber optics, 4–tuneable laser, 5–electro-acoustic vibrator drive, 6–electro-acoustic vibration generator, 7–TOP magnetic coils, 8–flexible vacuum pipe, 9–mirror, 10–ion pump, 11–trap magnetic coils (MOT), 12–telescope.
Experimental Apparatus Status
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References: