Low-Energy High-Precision Experiments

Standard Model

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Non-Newtonian Gravitational Interactions: Theory

- Newton's law of gravity (at large scale)

$$F = G\frac{m_1 m_2}{r^2}$$

$$V = -G\frac{m_1 m_2}{r}$$

where $G = 6.6743 \cdot 10^{-11} m^3/kg \cdot s^2$

- Yukawa-like modified potential (at small scale)

$$V = -G\frac{m_1 m_2}{r}(1 + \alpha \cdot e^{-r/\lambda})$$

where, α = Strength Factor
λ = Yukawa distance

Non-Newtonian Gravitational Interactions: Theory

- To learn more about α and λ we need to probe the small distance gravitational interaction of particles.
- We need a particle which
  - Heavy
  - Long-lived
  - Neutral
- Neutron seems to be the perfect candidate.

Non-Newtonian Gravitational Interactions: Theory

Consider a neutron kept on top of a mirror with mass density ρ_m in the presence of a gravitational field (g).

Since the distance we are probing is much smaller than the size of mirror we can approximate it with an infinite plane.

Force on neutron due to earth is:

$$F_E = G\frac{m_E m_n}{R_E^2} = \frac{4}{3}\pi G \rho_E R_E m_n$$

Force on neutron due to the mirror:

$$F_m = 2\pi \rho_m \alpha \lambda G \cdot e^{-z/\lambda} m_n$$

Non-Newtonian Gravitational Interactions: Theory

Thus the gravitational acceleration (g) of the neutron is given by:

$$\mathrm{g} = \mathrm{g_E} + \mathrm{g_m}$$

$$\frac{\mathrm{g_m}}{\mathrm{g_E}} = \frac{3}{2}\alpha \cdot \frac{\lambda}{\mathrm{R_E}} \cdot \mathrm{e}^{-\mathrm{z}/\lambda}$$

$$\implies \frac{\mathrm{g}-\mathrm{g_E}}{\mathrm{g_E}} = \frac{3}{2}\alpha \cdot \frac{\lambda}{\mathrm{R_E}} \cdot \mathrm{e}^{-\mathrm{z}/\lambda}$$

Thus by measuring the value of g, we can put constraints on the value of α and λ

Non-Newtonian Gravitational Interactions: Theory

In classical physics, we measure by directly calculating the acceleration of a ball falling under gravity.

However, neutrons do not follow classical physics. We need quantum physics.

$$(-\frac{\hbar^2}{2m}\nabla^2 + V(z))\psi = E\psi$$

where,

$$V(z) = mgz \text{ for } z > 0$$
$$V(z) = \infty \text{ for } z < 0$$

Non-Newtonian Gravitational Interactions: Theory

The (un-normalized) solution to the Schrodinger equation is:

$$\psi_n(z) = \mathrm{Ai}(\frac{z}{z_0} - \frac{z_n}{z_0})$$

where,

$$z_n = z_0(\frac{3\pi}{2}(n - \frac{1}{4}))^{2/3}$$

$$z_0 = (\frac{\hbar^2}{2m^2g})^{1/3}$$

$$E_n = mgz_n$$

Finding the value of z_n for various n will give us g.

Non-Newtonian Gravitational Interactions

Non-Newtonian Gravitational Interactions

- The Institut Laue Langevin (ILL), Grenoble, France

Non-Newtonian Gravitational Interactions: Experiment

- The ground state energy of the neutron is of the order of a few peV.
- Neutron mirrors make use of the strong interaction between nuclei and an ultracold neutron (UCN).
- We want the roughness of the mirror to be less than the de-Broglie wavelength of the neutron.
- For UCN the electromagnetic interaction with the mirror surface is of the order of 10^{-25}eV which is sub-gravitational and can be neglected.

Non-Newtonian Gravitational Interactions: Experiment

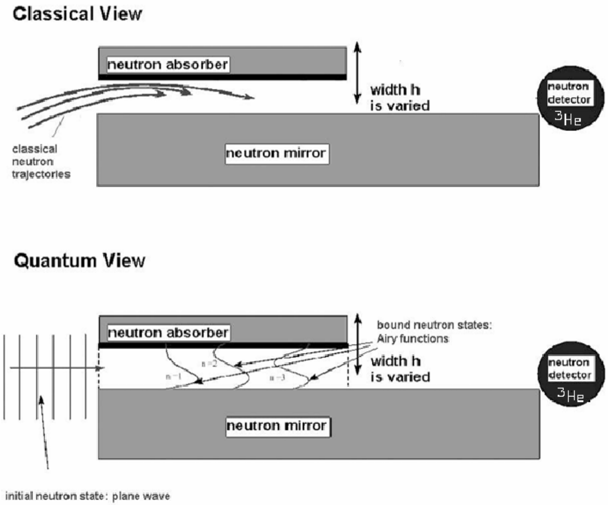
Table 1. from hot to ultracold: neutrons at the ILL

	fission neutrons	thermal neutrons	cold neutrons	ultracold neutrons	this experiment
Energy	2 MeV	25 meV	3 meV	100 neV	1.4 peV
Temperature	10^{10} K	300 K	40 K	1 mK	-
Velocity	10^7 m/s	2200 m/s	800 m/s	5 m/s	$v_\perp \sim 2$ cm/s

Non-Newtonian Gravitational Interactions: Experiment

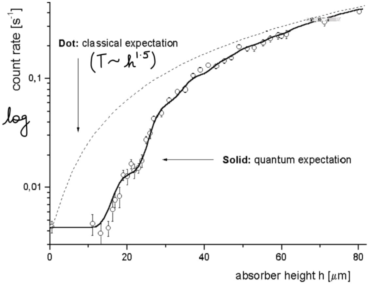
- We will be probing the scale where $3\mu\text{m} < \lambda < 10\mu\text{m}$
- The mirror has a roughness of about 2.2 ± 0.2 nm ($<< 50$ nm $<< 10\mu$m).
- We shall be using an absorber placed above the mirror to remove neutrons with high transverse energy.
- The absorber is made up of a rough glass ($\sigma = 0.75\mu\text{m}$) coated with Gd-Ti-Zr alloy.

Non-Newtonian Gravitational Interactions: Experiment



Non-Newtonian Gravitational Interactions: Experiment

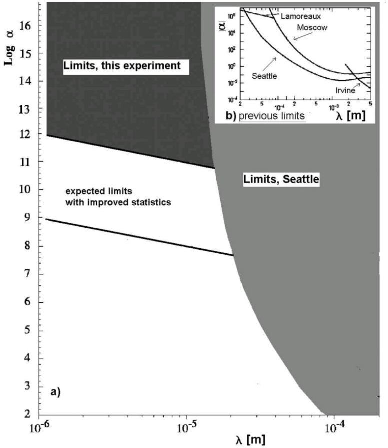
- A ^{3}He counter is used to measure the total neutron transmission (T).
- The absorber height is varied and T is measured as a function of h.



- No neutrons are observed below the height of 15μm

Non-Newtonian Gravitational Interactions: Experiment

- The results of the fit of potential to the measured data yield prediction for 90% confidence level exclusion bounds on α and λ
- The limit for α at $\lambda = 1\mu$m is 10^{11} and at $\lambda = 10\mu$m it is 10^{12}.



Non-Newtonian Gravitational Interactions: Future

- The neutron absorber used here has an absorption efficiency of 93% which can be improved in future to get stinger bounds on α and λ
- The limits can be further improved by an enhanced setup and improved statistics by new UCN sources as a Monte Carlo simulation shows.

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