INDIANA UNIVERSITY

HONORS THESIS

Investigations In Exotic Gravity

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Abstract

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Investigations In Exotic Gravity

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The strength of gravity pales in comparison to the other three fundamental forces of nature. This fact combined with the absence of an accepted theory of quantum gravity and with the well-known Planck length where the theory of gravity may change has made physicists skeptical about the validity of Newton's law of gravitation at quantum length scales. Many scientists have attempted to explain the reason for gravity's extreme weakness with no success. We describe the use of neutrons to probe for short range exotic gravity. We use data taken from various neutron scattering experiments to provide new constraints on the parameters α and λ_Y that describe possible Yukawa interactions at short distances.

Acknowledgements

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Physical Constants

Speed of Light	$c = 2.997\,924\,58 \times 10^{8}\,\mathrm{m\,s^{-1}}$ (exact)
Gravitational Constant	$G = 6.67 \times 10^{-11}\,\mathrm{m^3 s^{-1} kg^{-1}}$
Coulomb's Constant	$k = 8.99 \times 10^{9}\,\mathrm{Nm^2/C^{-2}}$
Permittivity of Free Space	$\epsilon_0 = 8.85 \times 10^{-12}\,\mathrm{m^{-3} kg^{-1} s^4 A^2}$
Boltzmann's Constant	$k = 1.38 \times 10^{-23}\,\mathrm{J/K}$
Planck's Constant	$h = 6.63 \times 10^{-34}\,\mathrm{m^2 kg/s}$

Chapter 1

Introduction

1.1 A Brief Example

To show just how weak the gravitational force is compared to the other fundamental forces of nature, we start by doing a calculation of the relative magnitudes of the strengths of the force of gravity and the Coulomb force experienced between two protons. The equations for both laws are shown below. The gravitational force between two objects of mass m_1, m_2 separated by a distance r:

$$F_G = G\frac{m_1 m_2}{r^2} \tag{1.1}$$

The Coulomb force between two point charges with charge q_1, q_2 separated by a distance r:

$$F_C = k\frac{q_1 q_2}{r^2} \tag{1.2}$$

Calculating these forces with the known values for these constants we obtain the following magnitudes for each force: $|F_G| = 5.78 \times 10^{-71}$ N and $|F_C| = 2.36 \times 10^{-28}$ N. The relative magnitude of these two forces is the cause for much of physicist's concerns for the validity of Newton's law of gravitation.:

$$|\frac{F_C}{F_G}| \approx 4.08 \times 10^{42} \tag{1.3}$$

This unfathomably large number sparked the curiosities of many physicists that eventually lead to the many theories that we will explore below. How can two apparently "fundamental" forces of Nature have strengths that are so different? The other two forces (the "weak" and "strong" forces) are much closer in size to electromagnetism than they are to gravity, so gravity really seems to be the outlier. It is also by far the weakest force, and we have many examples in the history of physics where an apparently weak force was later understood to be a residual effect of a much stronger force at short distances whose stronger effects somehow cancelled out at longer distances. The electromagnetic force between electrically neutral atoms, for example, is now known to be a small residual effect of the much stronger interaction between electric charges. Could the same somehow be true for gravity?

1.2 Alternative Theories of Gravity

1.2.1 Length Scale for a Quantum Theory of Gravity

A quantum theory of gravity has been theorized since the dawn of quantum mechanics. However, the construction of this theory has truly been elusive. The issue that arises first is the length scale at which physicists believe quantum gravitational effects will begin to become apparent. This length scale is hypothesized to be on the order of a Planck Length (l_P), which is defined using the three well known physical constants from relativity (c), quantum mechanics ($\hbar$), and gravity (G), as follows:

$$l_P = \sqrt{\frac{\hbar G}{c^3}} \approx 1.616 \times 10^{-35}\,\mathrm{m} \tag{1.4}$$

To put this number into perspective, the smallest distance sensed in a laboratory occurs in collisions at the Large Hadron Collider (LHC) in Geneva, Switzerland. The length scale probed in the LHC collisions is $\approx 10^{-19}$ m. The true significance of the daunting feat it will be to directly probe the Planck scale can be understood using Heisenberg's uncertainty principle.

$$\sigma_x \sigma_p \geq \frac{\hbar}{2} \tag{1.5}$$

The uncertainty principle can then be easily extended to show the relationship between the position and momentum of a quantum particle (I have chosen units such that $\hbar$ is one) is

$$\sigma_x \geq \frac{1}{\sigma_p} \tag{1.6}$$

In order to get to the Planck length scale, a photon must have an energy on the order of 10^{35} eV. A photon carrying such a large amount of energy localized to this distance would create a small black hole. We will have no idea if quantum gravitational effects will truly become apparent at this length scale until we can devise a way to get to reach such high energies. Maybe the Planck length scale is not really of any significance due to the fact that its value was derived from simple dimensional analysis. It could mean nothing at all, a mere number that nature haphazardly spit out. Or it could define the boundary of the mysterious realm of quantum gravity physicists have been theorizing for years. Only time will tell.

1.2.2 A Thermodynamic Approach

Gravity has interesting ties to thermodynamics and black holes. Einstein's famous field equations have been (re)derived from the thermodynamic equations for a black hole by University of Maryland Professor Ted Jacobson and others [4]. Stephen Hawking famously proved that black holes do indeed have a temperature and therefore emit radiation, while Bekenstein proved that the total entropy of a black hole is proportional to its surface area. Black holes are very mysterious and fascinating objects as they exist on the extreme end of both gravity as well as thermodynamics. No one really knows what happens to matter that enters a black hole. It was long thought that by throwing something into a black hole it would effectively erase that object from the universe. However, this would be a blatant violation of the second law of thermodynamics. This law states that the entropy of the universe always increases. If matter was erased from the universe, i.e. thrown into a black hole, it would decrease the entropy of the universe, contrary to the second law. This paradox went unanswered for many years, but it was indeed solved and the verdict was that the second law of thermodynamics is upheld. The entropy of the universe does not decrease when matter is thrown into a black hole. It is this calculation that we outline in this section. First, recall from Newtonian mechanics that the escape velocity, v_{Esc}, of a massive object can be found from the famous relation $\vec{F} = m\vec{a}$ as follows:

$$\vec{F} = G\frac{Mm}{R} \tag{1.7}$$

where M and R is the mass and radius of the planet respectively, and m is the mass of the object that is going to be escaping the planet. Since the object will be in orbit around the planet, it will have a centripetal acceleration, i.e.

$$F = ma = \frac{mv^2}{R} = G\frac{Mm}{R^2} \tag{1.8}$$

Now, $v = v_{Esc}$, then solving for v_{Esc} one gets the following relation

$$v_{Esc}^2 = \frac{2GM}{R} \tag{1.9}$$

This is the speed at which you would need to throw an object such that it would not be pulled back down to the surface of the gravitational body (for example, if you throw a baseball up at around 11.4 km/s, it won't come back down). This concept can easily be extended to black holes using the fact that they are so massive that light isn't fast enough to escape their gravitational pull. To put this in other words, the escape velocity of a black hole is greater than c. For the purpose of this derivation, we will set the escape velocity (1.9) equal to c:

$$c^2 = \frac{2GM}{R} \tag{1.10}$$

This wouldn't be a discussion on thermodynamics without involving the idea known as entropy. Before defining entropy, we need to define what are known as microstates. Microstates of a system are all of the possible configurations of the system under study. The set of microstates for a system is denoted Ω. For example, if our system were two arrows that could either point up or down independently, with each state defined as the orientation of each arrow, then this system would have four microstates ($\Omega = (\uparrow,\uparrow),(\uparrow,\downarrow),(\downarrow,\uparrow),(\downarrow,\downarrow)$). A key assumption of thermodynamic equilibrium is that each state is equally probable (consistent with possible macroscopic constraints). The general formula for entropy can now be written down if one assumes that the equilibration process drives a physical system to a condition in which we are maximally ignorant of its microstate. The equation for entropy becomes:

$$S = kln(\Omega) \tag{1.11}$$

The important property to notice about entropy is that it is proportional to the number of microstates, which is in turn always some quantity to the Nth power for N independent particles. Therefore the entropy is proportional to N.

$$S \propto N \tag{1.12}$$

Next we recall the famous waves that started the quantum revolution, matter waves. In 1924 Louis de Broglie proposed the existence of matter waves in his PhD thesis. In particular, de Broglie proposed the momentum of a particle was inversely proportional to its wavelength times Planck's constant:

$$p = \frac{h}{\lambda} \tag{1.13}$$

We must realize that the wave function of a particle in a black hole, which is spherical in shape, has to have a wavelength no larger than $4R$, since the wave function is not allowed to leak out of the black hole. R is the radius of the black hole (see Figure 1.1). We now move from de Broglie to Einstein. Einstein's famous relation $E = mc^2$ is now applied. Recall that for a photon γ:

$$E_\gamma = cp = \frac{hc}{\lambda} \tag{1.14}$$

With our constraint on λ, we can rewrite the above as

$$E_\gamma = \frac{hc}{4R} \tag{1.15}$$

Now we expect, given the very violent stellar collapse process that makes a black hole in the first place, that the black hole will have a very high entropy. The most efficient way to increase the entropy of a system is to partition its available total energy into the largest number of independent pieces possible. We therefore choose N to be the energy of the black hole divided by the energy of a photon:

$$N = \frac{mc^2}{\frac{hc}{4R}} = \frac{4Rmc}{h} \tag{1.16}$$

Now it can clearly be seen that the total entropy of a black hole is proportional to its surface area.

$$S \propto N \propto A \tag{1.17}$$

This means that when matter enters a black hole, it becomes a part of the black hole and the surface area of the black hole increases. This increase in surface area causes an increase in the entropy of the black hole, which means the total entropy of the universe did not decrease and the second law of thermodynamics can be upheld.

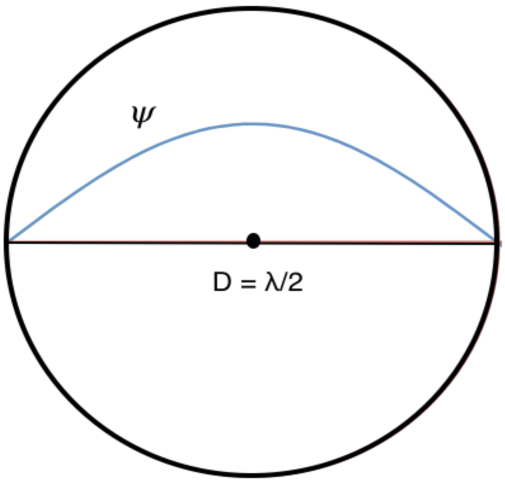

FIGURE 1.1: The smallest wavefunction that can fit into a sphere of radius R is $\lambda = 4R$.

This idea explains how the law of the increase of entropy of the universe can be upheld even in the presence of a black hole. However, the dependence of the entropy of the black hole on its surface area, rather than on its volume as for all other known objects in physics, is very strange. It has led to the so-called "holographic principle" idea which says that somehow the information content in a volume of spacetime should ultimately appear on its surface. We will not pursue this specific idea further but the attempt to explain this result "naturally" is one of the present intellectual trends in theoretical work on quantum gravity.

Chapter 2

Ideas for Modifications to Gravity at Short Distances

The extreme weakness of gravity poses the fundamental question that most physicists ask themselves. Is gravity really that weak, or are we simply unable to feel its true magnitude? This thought assumes that gravity is in fact on par with the other fundamental forces, but our instruments are simply not evolved enough to be capable of detecting it. Where might this other, much stronger portion of gravity go? We will explore this question in this section.

2.1 Brief Introduction of Spacetime

The concept of spacetime is important in most modern physics conversations, and is a part of the pioneering work completed by Albert Einstein. Since the main topic of this section is on the properties of spacetime, it would be helpful to have a precise and understandable operational definition of spacetime.

2.1.1 Spacetime and Gravity

Spacetime is a theoretical framework created by Einstein when he constructed the theories of special and general relativity. It comes from the idea that space and time are inevitably connected, the word is spacetime (not space and time separately) for a reason! It can be used to visualize how the force of gravity interacts with matter. Most renderings of spacetime show it as a two-dimensional sheet, which is sufficient for science popularization of the idea. However, in reality spacetime is four dimensional because we in fact live in a four dimensional universe (three spatial dimensions plus one time dimension). The main take away from Einstein's theories is the phenomenon that mass distorts spacetime, causing it to curve, and that particles moving in this curved spacetime have bent trajectories. In the absence of matter, spacetime is flat and particle motion is straight. These ideas are suggested visually in the figure below.

2.2 Extra Dimensions of Spacetime

As mentioned in the previous section, we currently understand spacetime as four dimensional. However, spacetime could in fact have many more "hidden" dimensions. Hidden in the sense that they are too small for instruments to perceive. To many this seems very absurd at first. However, after applying some very well known and accepted physical laws this idea seems much more plausible than most think. In fact, this idea can be reinforced using Gauss' law and the idea of flux.

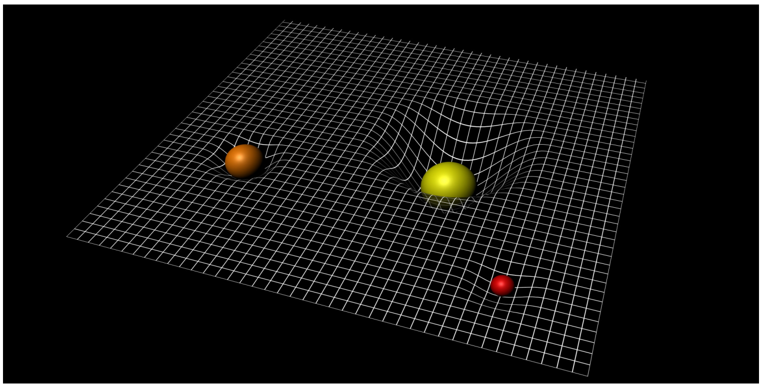

FIGURE 2.1: Two-Dimensional rendering of spacetime along with the effects massive bodies have on it.

2.2.1 Multiple Dimension Analog

Gauss's law famously states that the electric flux through any surface enclosing a net nonzero electric charge is proportional to $1/\epsilon_0$ multiplied by the total charge. This is described in the equation:

$$\Phi_E = \oint_S \mathbf{E} \cdot \mathrm{d}\mathbf{A} = \frac{Q}{\epsilon_0} \tag{2.1}$$

If the Gaussian surface is symmetrical (say a sphere) and if the spatial distribution of electric charge inside is also spherically symmetric, then the electric field is the same at all points along the surface, i.e. it is constant and can be taken outside of the integral. Meaning that we only integrate an infinitesimal unit of area which turns out to be the total surface area of the Gaussian surface. Since we chose our surface to be a sphere its area is $A = 4\pi r^2$, where r is the radius of the sphere. Therefore the electric field for a charge Q enclosed by a sphere is:

$$E = \frac{Q}{A\epsilon_0} = \frac{Q}{4\pi\epsilon_0 r^2} \tag{2.2}$$

We can extend this calculation to higher dimensions. As we saw above, the electric field of a point particle of charge Q is proportional to one over the radius of the Gaussian sphere squared. We make the extension to higher dimensions as follows. In the above example we were working in three spatial dimensions. We note that the area of a three dimensional sphere is proportional to r^{D-1}, where D is the dimension of the space that our Gaussian surface resides in. If we assume that Gauss's law should be true also in D spatial dimensions, we can make the following claim:

$$E \propto \frac{1}{r^{D-1}} \tag{2.3}$$

That is, the electric field E of a charge Q enclosed in a Gaussian surface that resides in D spatial dimensions is proportional to one over the radius of the Gaussian sphere to the $D-1$ power. Notice that forcing a field to flow into more dimensions decreases its strength.

Now the reason why it is reasonable to still "believe" Gauss's law in D dimensions is that, in combination with the other laws of magnetism and the ideas of relativity which give us Maxwell's equations, we can use it to derive the conservation of electric charge. Conservation laws are very rare in physics, so it is not hard to imagine that the conservation law of electric charge would still be true if we increased the number of spacetime dimensions to D. But the source for gravity is mass/energy, which is also conserved. So what happens if we imagine that gravity leaks into D dimensions?

2.2.2 Extension to Gravity

To show how this idea can be extended to gravity, we first start with Newton's law of gravitation:

$$F = \frac{Gm_1m_2}{r^2} \tag{2.4}$$

With the previous section in mind, we can directly identify that the gravitational flux modeled in this equation resides in the three spatial dimensions we all know and love. Gauss' law can be extended to the gravitational force in the following statement: the gravitational flux through any closed surface is proportional to the gravitational constant G multiplied by the enclosed mass.

$$\Phi_G = \oint_S \mathbf{g} \cdot \mathrm{d}\mathbf{A} = -4\pi GM \tag{2.5}$$

Another way to think about it is with a simple analogy. Think of a garden hose with a pinhole on one end, and a regular opening on the other. If water were to flow from the pinhole through the rest of the hose, the water would not travel directly along the wall of the hose at distances very close to the pinhole where the water originates. The water would travel in a three dimensional path before it reached the walls of the hose. However, if an observer was standing at the other end of the hose watching, they would report that the water was moving in only one dimension. The same idea can be applied to gravity. In our everyday lives, we are the observers at the end of the garden hose, only perceiving one dimension of the force. While there could well possibly new, exotic forces, in the regions we are not yet able to sense. See the figure below for a picture illustrating this situation. [3]

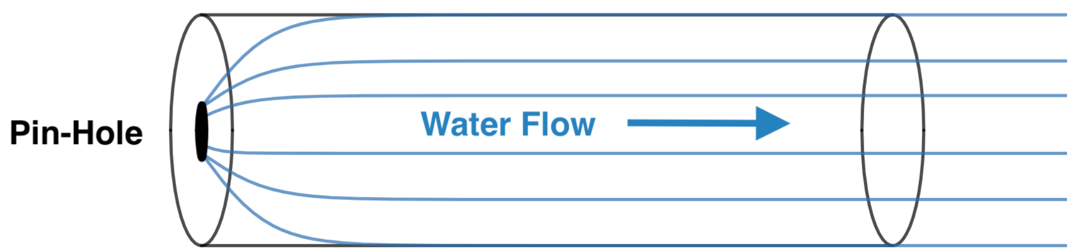

FIGURE 2.2: Garden Hose Example of Gravity [3]

Chapter 3

Properties of Neutrons

3.1 Why Use Neutrons to Probe Gravity?

Neutrons have a very small spatial extent of about 10^{-15} m, no net electric charge, and a very small electric polarizability, making them among some of the most delicate probes in experimental physics. Neutrons also have other properties that each have their own advantages and applications. These classes of neutrons, along with some of their many applications, are discussed below.

3.1.1 Slow Neutrons

A class of neutrons that are of particular importance for experimental work are known as "slow neutrons". For a neutron to be considered slow it has to have an energy around 25 meV or below. Slow neutrons are special because at this energy their de Broglie wavelength is near the atomic spacing in condensed matter. This is highlighted below:

$$\lambda = \frac{h}{p} \approx 10^{-10}\,\mathrm{m} = 1\,\text{Å} \tag{3.1}$$

This kinetic energy is also low enough that it does not ionize matter. This means that slow neutrons can pass through large amounts of matter and also be coherently scattered, making them a versatile and important tool for many precision experiments. **Dubbers2011**

3.1.2 Small Electric Polarizability

The neutron electric polarizability quantifies how hard it is for the quarks inside of a neutron to become separated spatially. This very small value of the neutron electric polarizability comes from the insanely strong force between the quarks making up each particle from the strong interaction. Remember that an up quark has a charge of $+2/3e$ while the charge for a down quark is $-1/3e$. A neutron is composed of one up and two down quarks, giving it a net electric charge of zero. A proton consists of two up quarks and one down quark, giving it a total electric charge of positive one. The dominant force acting on the quarks is the strong nuclear force. The neutron is essentially invisible to the other more dominant forces of nature at the length scales that will be probed in this experiment. Therefore, the most prominent force they will feel is that of gravity, which is all we care about in this measurement. [2]

Chapter 4

The “Exotic" in Short-Range Exotic Gravity

In field theories a fundamental class of particles known as exchange bosons give rise to forces between other particles. The exchange of these force-carrying bosons is what transmits the force. When searching for a new force, we are in fact searching for a new type of exchange boson. The existence of such a boson can be proven in many ways. If a boson exists, it will interact with matter by transmitting a force, which generates an effective potential. We are searching for a new potential that could have only been generated from a new boson.

With all of the foundations in place, it is time to dissect the details of the experiment we are conducting by explicitly stating what we are looking for, and how this is related to exotic gravity. First, when referring to a force as “exotic", this means it behaves differently than what our accepted theories predict. In our case, gravity has been widely observed to follow Newton's Law of Gravitation. Two nonrelativistic particles with masses m_1 and m_2 separated by a distance r interact with a potential energy given my Newton's law.

$$V_{Newton} = -\frac{Gm_1m_2}{r} \tag{4.1}$$

With the discussion on bosons above in mind, the effective potential generated by this new boson would change with distance in a different way from what we would expect based on this formula, i.e. it feels a force where is shouldn't. Since our range is on the order of atomic scales, we are interested in the regime were neutrons and protons interact. Due to the $1/r^2$ nature of the gravitational force, its magnitude increases as r tends to zero. A larger gravitational force at short distance, where there is little experimental data to guide us, would give rise to a stronger exotic force (if one exists). This exotic force could have a very short range. We are concerned with short-ranges on the order of 1 Å for our exotic gravity search using neutrons.

4.1 The Yukawa Potential

Hideki Yukawa, a Japanese physicist, won the 1949 Nobel Prize in Physics for the prediction of the meson, a force carrying boson for the nuclear force. The massive nature of the meson gave rise to a finite range for the strong nuclear force. In fact, the exponential damping of the strength of the interaction in the Yukawa potential expression arises from the fact that if a quantum particle at rest emits an exchange boson of finite mass, thereby “temporarily" violating the conservation of energy (this is allowed by the time-energy uncertainty principle of quantum mechanics as long as energy is conserved in the overall final process), then the wave function for this process will be exponentially suppressed. This gave rise to the Yukawa potential, which has the form

$$V_{Yukawa} = -g^2 \frac{e^{-mcr/\hbar}}{r} \tag{4.2}$$

Where g is a scaling constant, m is the mass of the particle, and r is the radial distance to the particle. If the mass of the exchange boson $m = 0$, the Yukawa potential reduces to a simple constant over r potential, such as in electromagnetism with the photon. The range of the Yukawa potential is inversely proportional to the mass of the exchange boson. This is where the well known fact of the infinite range of the electromagnetic force comes from. The photon's mass is zero, making the range infinite. Therefore, if the exchange boson has a nonzero mass it will have a finite range.

Some believe that at short distances gravity may have an additional Yukawa term in addition to the Newtonian term, giving rise to the Newtonian potential plus an extra exponential correction factor. This factor is characterized by two constants α and λ_Y that parametrize the strength and range of some new (exotic) Yukawa interaction relative to gravity. The range is set by the mass of the new exchange boson that generates this new potential.

$$V_{Yukawa} = -\frac{Gm_1m_2}{2}[1 + \alpha e^{-r/\lambda_Y}] \tag{4.3}$$

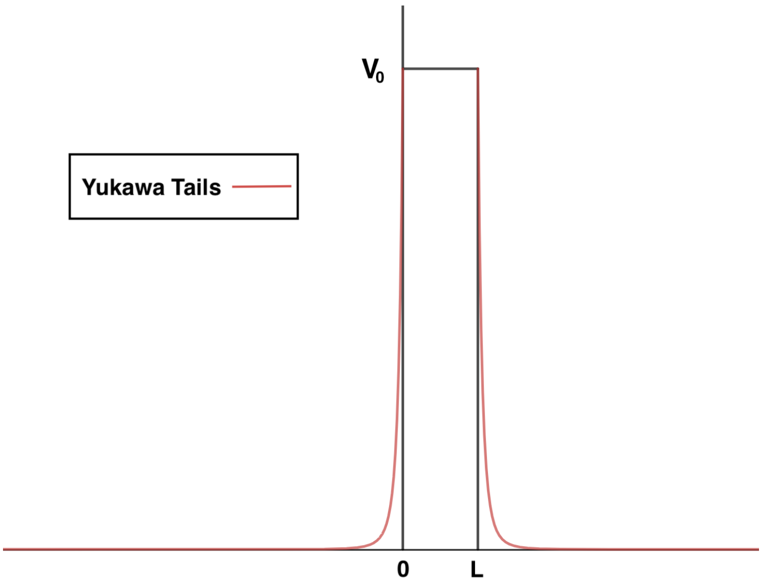

FIGURE 4.1: Yukawa Potential [Desmos]

These Yukawa tails seen in the above figure are what we are looking for experimentally. In neutron interferometry, where the neutron passes all the way through a mass in one arm of the interferometer, we see two such Yukawa tails in the phase shift of the neutron's wave function, whereas in gravity refractometry, where the neutron reflects off of a flat mirror surface, we only see one. By subtracting the scattering amplitudes measured by these two different techniques we are able to isolate the Yukawa interaction. Due to the high precision of the experiments, we can place better constraints on possible new Yukawa interactions of the neutron with matter. This is discussed further in the Experiment section below.

Chapter 5

Neutron Interferometry & Gravity Refractometry

5.1 Neutron Interferometry

An interferometer works by measuring the interference of the quantum wave functions of two beams. Interferometers have been in scientific use for centuries, and some of the most prominent scientists used them to reveal the mysteries of nature due to the precise measurements interferometers can produce. Perhaps the most famous example is the Michelson interferometer, which helped disprove the existence of the mysterious luminescent ether when it failed to see the phase shift of a light wave that should have occurred as the Earth moved through the ether. Although at the time Michelson was convinced that his experiment, conducted near the end of the 19th century at Case Western Reserve University in Cleveland, Ohio on a rotating platform resting in a pool of liquid mercury, was a complete failure since it failed to see the ether, we now know of course that this is the “right" answer according to special relativity. The most well known recent example of an important interferometer experiment is of course the discovery of gravitational waves, which were detected a few years ago using a device very similar in concept to Michelson;s device.

Neutron interferometers consist of three equally spaced, perfect silica crystal blades cut from a single highly perfect crystal. A neutron beam is incident on the first crystal, this incident beam is split into two by diffraction of the neutron deBroglie waves from the crystal lattice planes before encountering the second crystal. The second crystal brings these two split beams together to hit the third and final crystal. The two separate beams are then shot out the back of the interferometer, where various neutron detectors will be waiting. A schematic of a general neutron interferometer is shown below:

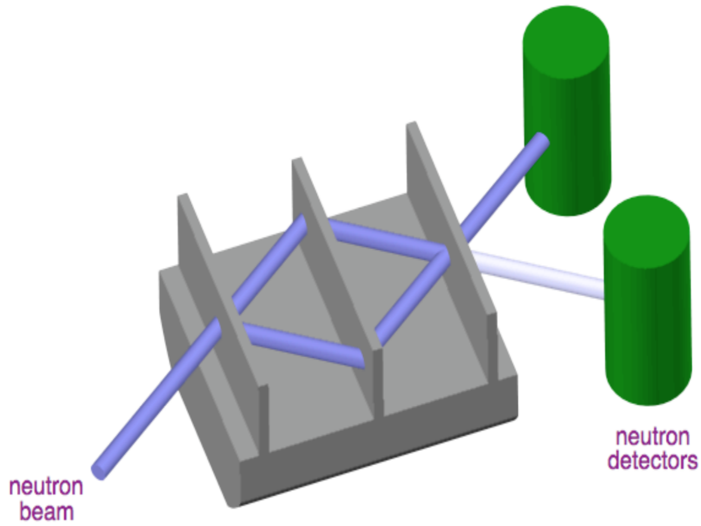

FIGURE 5.1: General Layout of a Neutron Interferometer

The above figure is a fairly generic interferometer configuration. Depending on the needs of the experiment, interferometer with a wide variety of crystal arrangements can be deployed. The image below shows some examples of different configurations of neutron interferometers. The main aspect of utilizing neutron interferometry relevant for our work inexotic gravity is the fact that neutrons undergo no net momentum transfer as they pass through the phase shifting mass in the interferometer path.

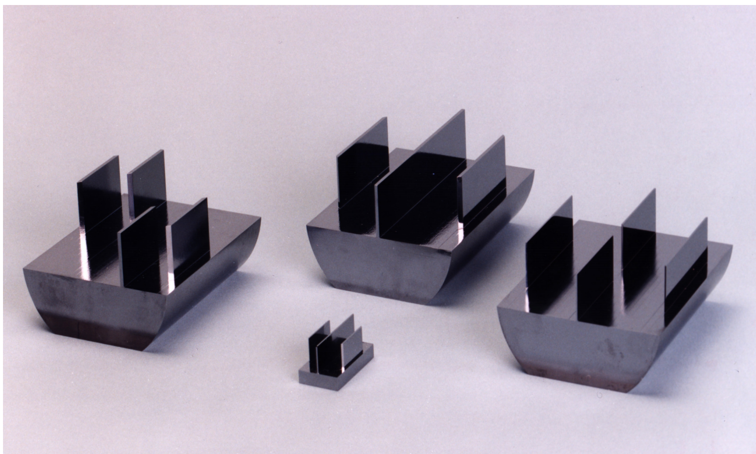

FIGURE 5.2: Various Neutron Interferometer Configurations

5.2 Neutron Interferometry and Gravity

We have already explored why neutrons are extremely useful objects for precision experiments due to their zero net electric charge, extremely small electric polarizability, and ability to coherently interact with matter to allow for delicate measurements of its quantum wave function. We now explore how we use neutrons to probe for exotic gravity. To do this we will need to utilize some somewhat complicated principles from quantum mechanics and wave phenomena.

5.3 Quantum Mechanics: The Potential Barrier

When the wave functions of neutrons interact with finite potential barriers they are slightly altered. When a particle's wave function encounters a potential barrier, a portion of the incident wave function will be transmitted, and a portion will be reflected. The amplitudes of the transmitted and reflected waves are determined by the wave amplitude solutions coming from the solution of Schrödinger's equation using the boundary conditions and the initial conditions.

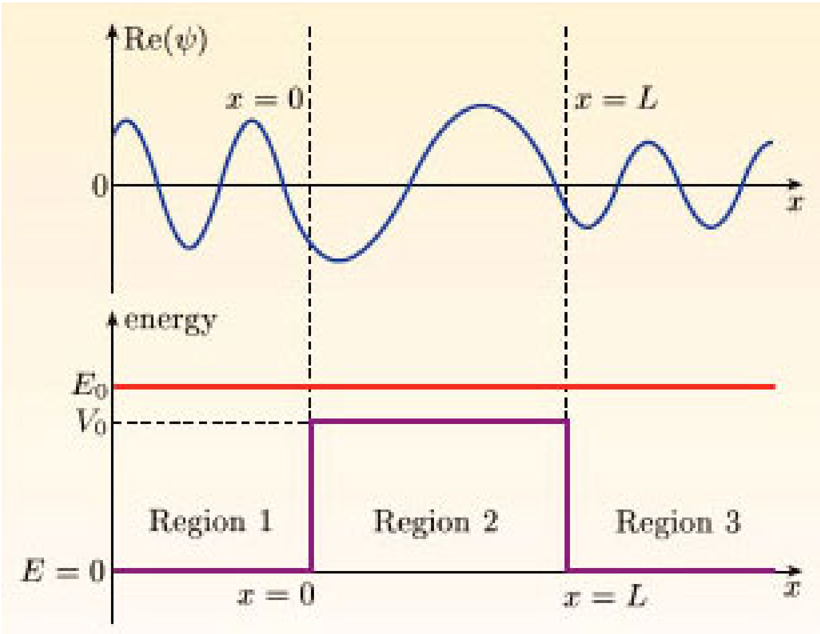

FIGURE 5.3: Interaction between the wave function of a quantum particle and a finite potential barrier [Open University]

5.4 Wave Phenomena: Phase Shits

When the wave function of a quantum particle interacts with matter it changes slightly. Depending on the character of matter it is interacting with, it could change the amplitude, frequency, or absorb the wave function. The main change that we are concerned with in this analysis is the phase shift of the neutron wave function. A phase shift is the degree with which the wave has been shifted, either forwards or backwards relative to some unshifted standard, by some angle Φ. This can clearly be seen in the above figure.

5.5 Gravity Refractometer

Gravity refractometry was originally developed as a way of measuring neutron scattering amplitudes for various elements in the 60's and 70's to high precision. It involves sending neutrons produced in a reactor downs a long, vacuum chamber in a horizontal direction from a known height. At the end of the long passages lays a very flat mirror (See below).

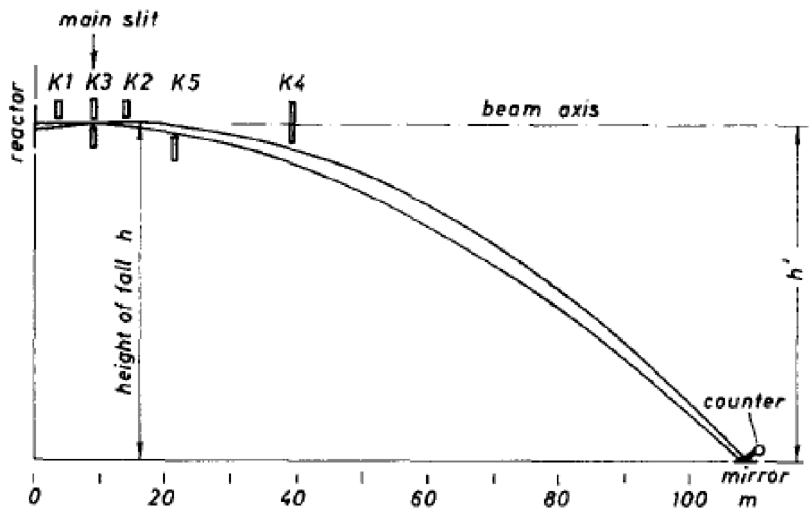

FIGURE 5.4: Schematic of a Gravity Refractometer [1]

We all know that a massive object falling in a gravitational field will follow a parabolic path. The same is true for neutrons. We also know that if you hold an object a height h above the Earth's surface, this object will have a potential energy equal to the objects mass (m) multiplied by this height (h) as well as the acceleration due to gravity (g). Therefore:

$$V = mgh \tag{5.1}$$

Knowing the height that the neutron started at, we have an accurate value for the gravitational potential energy of the neutron. If you recall from above, the initial potential energy of the neutron (i.e. the height) determines the momentum that the neutron has when it strikes the mirror and therefore in turn the probabilities for the incident wave function to be reflected or transmitted from the mirror. Koester and colleges found that the reflectively of the neutron decreased as a function of the height above a critical height which depended on the mirror material (see Fig. 4.4 below). This critical height determines the neutron optical potential of the matter. The main aspect of gravity refractometry that will be utilized in this paper is the fact that the neutron undergoes a non-zero momentum transfer upon reflection.

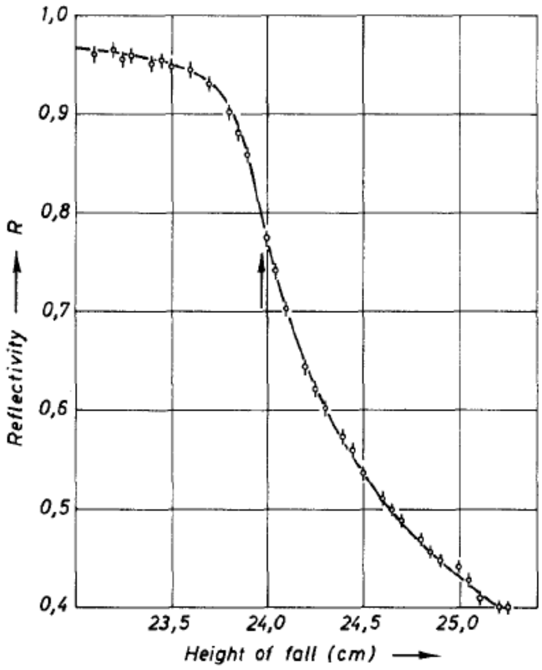

FIGURE 5.5: Reflectively of Toluene (C_7H_8). Full Line: calculated curve for $h'_0 = 23.955$ cm [1]

Chapter 6

Experiment

The goal of our reanalysis of this experiment is to provide new constraints on the constants α and λ_Y that parametrize the theorized new short-range Yukawa interaction. We do this by compiling data from two different experiments that were originally performed to measure the scattering amplitudes of various elements using two different methods, Neutron interferometry (NI) & Gravity refractometry (GR). The previous analyses of these experiments were conducted without incorporating the possible Yukawa interaction. We reanalyzed this data with the possible Yukawa interaction term to try and find new constraints on the parameters α and λ_Y. The general idea is to isolate the Yukawa interaction by subtracting the phase shift of the neutron wave function from both interferometry as well as gravity refractometry.

$$\Delta\Phi_{Yukawa} = 2(\Phi_{NI} - \Phi_{GR}) \tag{6.1}$$

This relation comes from the following phase shifts for the neutron wave function undergoing scattering through interferometry and gravity refractometry respectively.

$$\Delta\Phi_{NI} = \Phi_{n-A} - \Phi_{Yukawa} \tag{6.2}$$

$$\Delta\Phi_{GR} = \Phi_{n-A} - \frac{1}{2}\Phi_{Yukawa} \tag{6.3}$$

We used various data analysis frameworks to conduct the data analysis, mainly Python and ROOT. Our results are displayed in the plot below.

Chapter 7

Results, Conclusion, & Future Work

7.1 Results

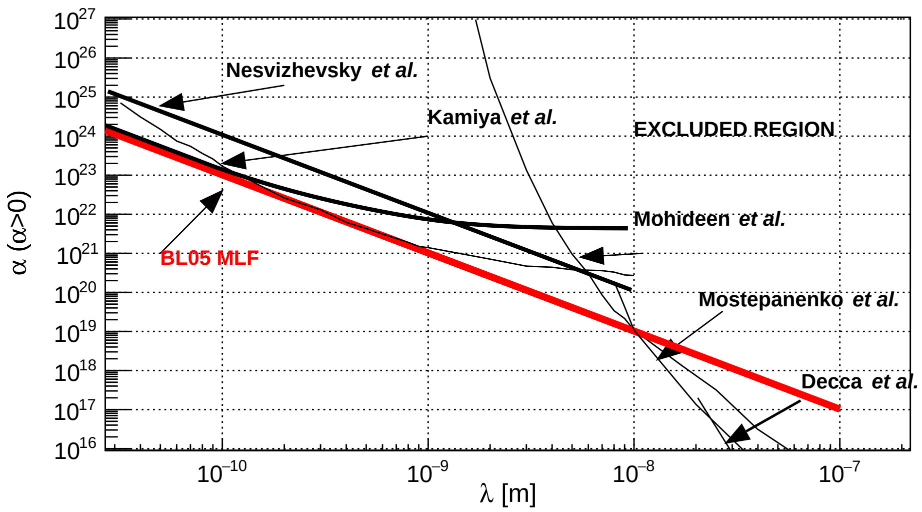

FIGURE 7.1: New limits on α and λ

7.2 Conclusion

We were able to improve the constraints on α and λ_Y such that they were able to beat other measurements using different techniques (see Fig. above). So although we have not discovered any evidence of short-range exotic gravity, we have succeeded to further restrict the possibilities.

7.3 Future Work

The gravity refractometer designed by Koester and colleagues provided a large source of high-precision data for us to analyze in our search for possible exotic short-range gravity. A different experimental setup is now under development which can be used to improve the accuracy of the neutron mirror measurement of neutron optical potentials by about two orders of magnitude. The main source of error in the Koester experiment is the accurate knowledge of the height of the neutron. The incident neutron is created from a beam produced by a reactor. This beam has a finite thickness, and it is difficult to determine precisely where exactly the neutrons are located within this thick beam. The height of the neutron is of great importance in the measurement since that is the main parameter determining the potential energy of the neutron.

One way to get around this beam thickness issue is to get rid of the beam all together. The new approach is as follows: spill Ultra Cold Neutrons (UCNs) on a very flat granite table. The UCNs will bounce on top of the table, and the height of their bounce is very small (about 10 microns) which is much smaller than the precision that Koester was able to determine for the average height of the neutron beam used in his work. We will then gently push the neutrons off of the table and let them bounce off of a mirror located directly below the table. Instead of shooting neutrons across a room and measuring how far they fall, we will construct a table of known height and simply push the neutrons off. The greater precision of this new table set up arises from the greater precision of the height over which the neutrons will fall.

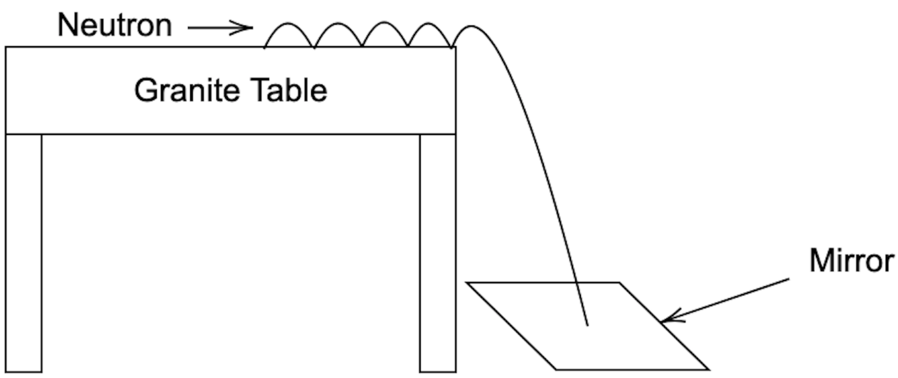

FIGURE 7.2: Experimental Set-Up [MathCha.io]

Bibliography

[1] L. Koester and W. Nistler [*New Determination of the Neutron-Proton Scattering Amplitude and Precise Measurements of the Scattering Amplitudes on Carbon, Chlorine, Fluorine, and Bromine*]. Z. Physik A 272, 189-196 (1975)

[2] Dirk Dubbers and Michael G. Schmidt [*The Neutron and its Role in Cosmology and Particle Physics*]. arXiv 18 May 2011, extended version of: Reviews of Modern Physics, in print.

[3] Lisa Randall *Warped Passages: Unraveling the Mysteries of the Universe's Hidden Dimensions*. Ecco; Later prt. edition (2005)

[4] Ted Jacobson [*Thermodynamics of Spacetime: The Einstein Equation of State*]. Phys.Rev.Lett.75:1260-1263,1995