Cavendish Experiment Proposal

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This proposal has been prepared by

Brian C. Ferrari, Team Leader

with the help of

Cody Jordan, Ryan Sirimanne and Ahad Bawany

In behalf of the

Society of Physics Students at the University of Central Florida

Abstract

To better prepare for graduate school we, the Society of Physics Students at the University of Central Florida, want to conduct the Cavendish Experiment. By measuring the displacement of a torsion bar caused by the gravitational force between two masses on each end we can calculate the gravitational constant.

I. Introduction

In this proposal we will request funding for the recreation of the historic Cavendish experiment. First we will outline the importance of the Cavendish experiment both in its historical context along with its current importance. In the next section we explain the procedure first done to conduct the Cavendish experiment followed by our procedure for the experiment. Finally we outline the equipment needed and what it will be used for in the experiment.

We will be recreating the historic Cavendish experiment with slight modifications thanks to advancements in technology. Recreating this experiment will give us the opportunity to learn valuable skills that we will need when we move forward into graduate school programs for experimental physics. This project will teach us how to design, construct and conduct an experiment on our own which will give us an edge when we begin work on our experiment for our PhD dissertation. We will also gain experience while conducting this experiment, since as most experimental physicists will agree no experiment goes according to plan on the first try. We will learn how to find solutions to errors in our experiment which is an extremely useful skill for us to have before moving forward into our graduate studies. Working in a group of our fellow peers while we conduct this experiment will be helpful for us to develop teamwork skills. This experiment will require us to design and conduct an entire experiment which is something most undergraduate physics programs don't offer their students the opportunity to do. We will also be working in the physics department machine shop which is common to do during a graduate experimental physics degree but not common to see done in the undergraduate level.

We can also use this project as an opportunity to better our presentation skills by reaching out to local high schools and offering to give a lecture on the history of this experiment as well as explain our process creating and conducting the experiment. This can be mutually beneficial to us and the students at the local high school by offering them a way to better see how physics research is done. Typically high school physics classes generally focus more on the calculations done in physics with only minor experiments shown. This might even help to inspire more young students to major in physics and possibly one day become researchers.

II. History of Cavendish Experiment

Robert Hooke was the first to suggest that the gravitational force felt by an object was proportional to the inverse square of its distance from the object causing the force. It was then Isaac Newton who mathematically derived Kepler's three laws of planetary motion. In deriving them he found that the force of gravity to be proportional to the product of the two masses divided by the square of the distance between them. To balance this equation a constant was needed although Newton himself did not find the constant. Equation (1) shown below is the current form found by Newton of the gravitation force (F) caused between masses (m) and (M) when at a distance (r) apart. The gravitational constant (G) was never calculated for but later was experimentally found.

$$(1) \qquad F = \frac{GmM}{r^2}$$

Henry Cavendish was the first to yield accurate values for the gravitational constant; this was a major breakthrough. This experiment was first performed in 1797-1798 by using a torsion balance made from a six-foot wooden rod suspended from a wire. Connected to each side of the rod was 0.72kg lead balls, suspended by a separate system was two 158kg lead balls positioned on alternate sides of the rod. This experiment has become the cornerstone of gravitational physics experiments and has continued to be used with modern technological changes. One of which being done by two researchers at University of Washington, Steve Merkowitzz and Jens Gundlach, have been able to reduce the uncertainty of the gravitational constant to 6.67390 x 10^{-11}.

III. Setup of Cavendish Experiment

As mentioned before Cavendish's experiment was done by having a torsion balance hung from a system of pulleys, at each end of the torsion bar there was a 0.72kg lead ball. Form another system of pulleys there was another torsion balance with a 158kg balls hanging from each end of the bar. The larger balls were place 9inchs away from the smaller balls each on opposite sides of the smaller balls so that their faint gravitational force would cause a torque on the balance of the smaller balls.

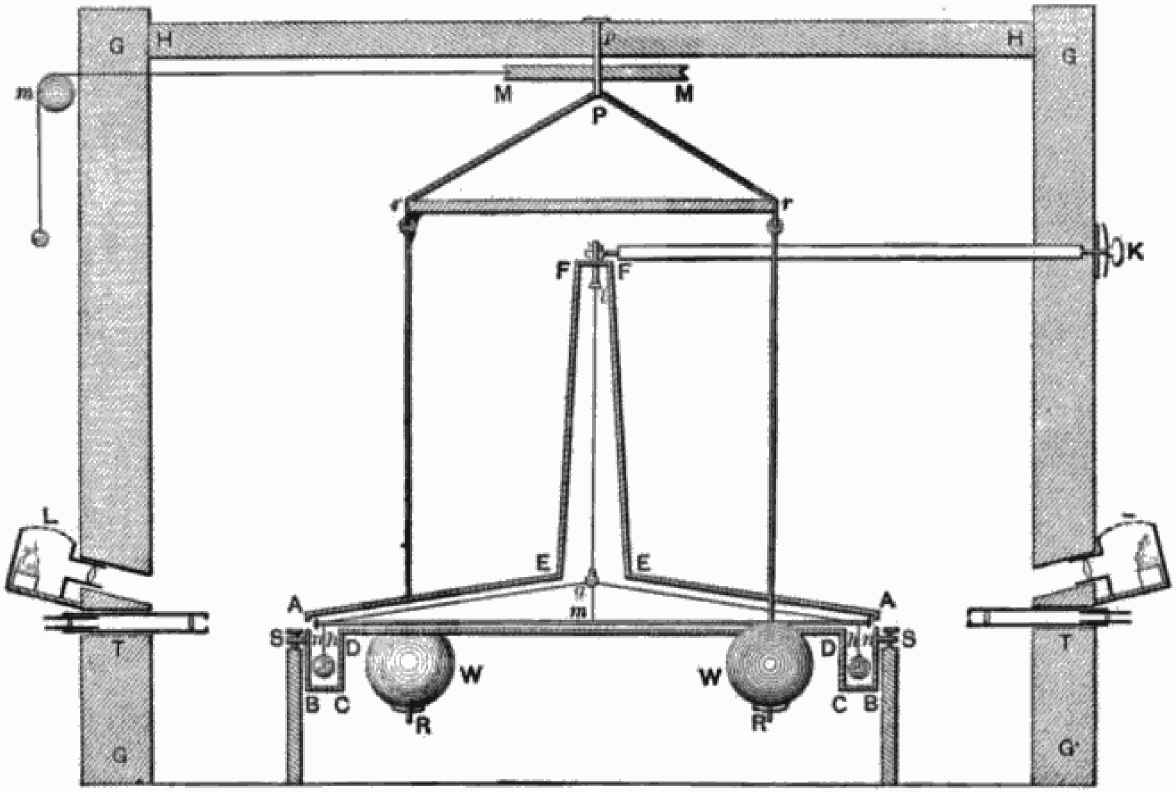

Fig. 1

The larger lead spheres caused an attractive force on the smaller spheres resulting in a torque being applied to the torsion bar and twisting the wire. Similarly to how a spring has potential when compressed a wire has a potential when twisted, for Cavendish to derive G he set the potential (equation 2) equal to the torque force the gravity (equation 3) of the larger spheres caused on the smaller spheres.

$$\tau_p = k\theta \quad (2)$$

$$\tau = FL \quad (3)$$

Where (k) is the torsion coefficient, (θ) is the displacement of the angle from the staring position to the equilibrium position, (F) is equal to the equation 1 and (L) is the length of the torsion bar. The inertia of the smaller spheres when being attracted by the larger spheres causes there to be an oscillation about the point of equilibrium. This oscillation can be used to experimentally find the torsion coefficient of the wire being used through equation (4).

$$(4) \qquad T = 2\pi\sqrt{\frac{I}{k}} \quad => \quad k = \frac{4\pi^2 I}{T^2}$$

Where I is the moment of inertia and T is the period of oscillation. The moment of inertia is simply the moment of inertia of a dumbbell system with a rod of negligible mass which is shown in equation (5).

$$(5) \qquad I = \sum_{i=1}^{2} m_i (r_i)^2 = 2m\frac{L^2}{4} = m\frac{L^2}{2}$$

Setting equations (2) and (3) equal to each other replacing (F) with equation (1) and (k) with equation (4) then solving for G Cavendish was able to derive equation (6).

$$(6) \qquad G = \frac{2\pi^2 L r^2 \theta}{MT^2}$$

Then experimentally finding each of the necessary values for the equation Cavendish was able to solve for G where he arrived at the value 6.74 x 10^{-11}.

IV. Our Procedure

This experiment centers around a rod of negligible mass compared to the two balls attached to the rod's ends. The two balls will be made of aluminum and have mass of 50 grams each. In the following, I will refer to the component balls-rod as the dumbbell. We will build an aluminum support system to hang the dumbbell from. This support system will consist of a base with rubber padding to prevent vibrations from interfering with the experiment. From the base there will be a rod that goes up to certain height, then will have another rod attached to it at a 90 degrees angle to ensure the dumbbell is hanging perpendicular to Earth's gravitational force. This will ensure the rod that the Earth's gravity does not affect the experiment. The support system will include a wire attached to its end hanging vertically, holding the dumbbell system from its center of mass. At the center of the dumbbell, we will attach a polished one sided mirror, that will allow us to precisely measure the rotation of the dumbbell with the use of a laser. Underneath the hanging dumbbell, the base of the apparatus will be placed. This will be a circular aluminum plate with rubber bottom to attenuate any vibrations from the surroundings which may interfere with the experiment. The top of this circular base plate will have a female groove along with a tapped hole at the center. Another circular aluminum plate will be placed on top of the first such that it has a through hole allowing the two plates to be connected with a screw In addition, the second place will carry a male extrusion fitting the grove of the first plate, allowing the two to rotate relative to each other. The top plate will also have two mounts for the larger 3kg mass tungsten balls which will be placed so their centers are the same distance apart as the smaller balls. The relative rotation of the plates will allow us to move the larger balls from a location that they have virtually no effect on the smaller balls to a second position that will cause the dumbbell to experience torque from the balls' gravitational attraction. This torque will angle the mirror causing the laser to be deflected which in turn we will measure using a position sensitive detector (PSD).

V. Budget

For the experiment we will need two 2.75” diameter (3kg) tungsten balls along with base mounts for them. These can be purchased from Midwest Tungsten Services, both balls and mounts. We will also need to purchase aluminum stock to be machined in the University of Central Florida’s Physics machine shop. Machining the aluminum into the top and bottom circular plates will require some of the funds to be used for the machine shop use fee. The plates will be machined in a vertical miller machine from circular stock. Then a groove will be made into the bottom plate and an extrusion matching that groove will be made into the top plate. Subsequently the plates will be drilled through the center to allow for a screw to hold them together. The top plate will have a through hole to allow for it to rotate along the groove. From the aluminum stock we will build the support system that will suspend the torsion bar holding the smaller masses this will again require machine shop time. The support system will be made by first attaching two rectangular stock pieces at a perpendicular angle, then machining a base for this support system that will allow for it to stand on its own while also holding the torsion bar. The torsion bar will be made from a less dense polycarbonate material which is already available to us. This will be machined into a thin rod with a groove on each side to hold the premade 50-gram aluminum balls in place and a mirror attached to the center of it. This torsion bar will be attached to the support system by the wire which we also have available already.

Next we will be set up the one dimensional PSD and connect it to the signal processing module. This will be done by connecting our 1D-PSD to a signal processing circuit board. We will then make a holder for it so that it can be placed directly above the laser emitter, ensuring that both have the center in the same place. We will make a holder for the laser emitter as well so that it can rest at an angle, ensuring that when it bounces from the mirror it will be deflected back to the 1D-PSD which will be placed directly above the laser emitter. This way the rest position will be when the laser is in the center of the 1D-PSD. The data from the 1D-PSD will be gathered on a computer so that when the experiment is conducted we will have a graph showing us the position of the laser over time, with center being our rest position and then we can determine the equilibrium position and oscillation periods from the graph to use in our calculations to determine the Gravitational Constant. Funds that exceed the grant amount have already been acquired for us by our sponsor.

VI. Summary

In this proposal we have described how the gravitational constant was initially proposed by Isaac Newton during his mathematical derivations of Kepler's three laws. It wasn't until Cavendish devised his experiment that the gravitational constant was calculated. We have explained how Cavendish originally conducted his experiment, as well as how we will be conducting our version of the experiment. This proposal has also outlined the necessary equipment along with its purpose for the experiment. We have also outlined the benefits that come from us performing this recreation of the Cavendish experiment. The experience we will gain to help us with our future endeavors in graduate programs will be invaluable. We will have the opportunity to perform outreach at local high schools with this experiment.

For those purposes we request the full funding of two thousand dollars to conduct this experiment. An additional small amount will be provided by the Physics Department at UCF.

VII. About the leader of the proposal

Brian Ferrari has been an undergrad student at the UCF since 2014. He is pursuing a double major in physics and math. During his time as a student, besides performing his school work, he has become a competent machinist. He has learned to work metals and wood and create pats for experimental apparatuses. This has enabled him to build many important pieces for the experimental research of various faculty of the Department of Physics at UCF, as well as large-size demos for the classrooms. He has also served as an Assistant of the Head of the Machine Shop. In this role, he has introduced the equipment to new students who wish to operate the machinery as part of their research. He will thus be the instructor for the members SPS at UCF to help them build parts of the proposed apparatus. None of the other undergraduate students has currently any knowledge of how to use the machines at the Machine Shop.

VII. Bibliography

- *Cavendish, Henry (1798). "Experiments to Determine the Density of the Earth". In MacKenzie, A. S. Scientific Memoirs Vol.9: The Laws of Gravitation. American Book Co. (published 1900). pp. 59–105. Retrieved 2013-12-30.* Online copy of Cavendish's 1798 paper, and other early measurements of gravitational constant.
- Y.T. Chen and A. Cook, *Gravitational Experiments in the Laboratory*, (Cambridge University Press, 1993)
- Boys, C. Vernon (1894). "On the Newtonian constant of gravitation". *Nature*. **50**
- Clotfelter, B. E. (1987). "The Cavendish experiment as Cavendish knew it". *American Journal of Physics*.

VII. Some Pictures from the Machine Shop showing B. Ferrari Working and Teaching