Creating a version of the Tolman-Stewart Experiment for use in an Intermediate Physics Laboratory Course

by

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This thesis has been reviewed by the senior thesis committee and the department chair and has been found to be satisfactory.

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THE ABSTRACT OF THE THESIS OF

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Thesis Title: *Creating a version of the Tolman-Stewart Experiment for use in an Intermediate Physics Laboratory Course*

The charge to mass ratio of an electron in a metal is widely used in many different scientific fields. It was first determined accurately by Richard C. Tolman and T. Dale Stewart in 1916. It is important for aspiring engineers and physicists to understand the origins of this important number in order to understand its impact on physics. Ithaca Colleges Intermediate Physics Laboratory class allows students to perform both modern and classical experiments. This gives the students the unique experience of discovering important constants in physics, as well as giving them important laboratory experience. The Tolman-Stewart experiment was recreated for Intermediate Physics Laboratory through the use of modern measuring devices and materials. Following a similar design as Tolman and Stewarts, the device spins a coil of copper wire at 5000 RPM and stops it in less than a second. The electrons, which are mobile inside of the copper, will continue to move and create a current. From this current, the charge to mass ratio of an electron can be determined.

ACKNOWLEDGMENTS

This project has had the help of many people. Dr. Kelley D. Sullivan helped with the new theory, building the device, and programming. Dr. Michael Rogers was the initial advisor to Judith Olsen '10 who both got the project started and gave it most of its present form. Students Alex Viola '13 and Julia Russ '14 both worked on the project and helped develop some of the modern features of the device. Professors Dr. Bruce Thompson and Dr. Dan Briotta helped with finding and elimination sources of noise as well as assisting in the development of the circuit that is used today.

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Chapter 1

Introduction

1.1 History

1.1.1 Origins of charged particles

Through his experiments, Benjamin Franklin discovered that electrical charge was held in positive and negative quantities and that electricity could only be transferred from one object to another. One of the experiments performed involved a glass rod and some cloth. [1] When the rod was rubbed with the cloth, the rod could then be used to electrify different objects. He did this by observing the attraction forces between the charged objects. He also learned that charge could not be created through friction which led, to what we call today, the principle of conservation of electric charge. Franklin was the first person to call the different charges positive and negative, although, unfortunately, he did not label them in a way that would be convenient later on.

More than a century later, physicist Arthur Schuster experimented with charged metal plates parallel to cathode rays. [2] Cathode rays occur when a voltage is applied between two electrodes equipped on a vacuum tube. [12] He applied an electrical potential between the plates and saw that the rays deflected towards the positive plates, providing evidence that cathode rays carry a negative charge. The name "electron" was coined in 1894 by George Johnston Stoney and the name began to be associated with cathode rays in the late 1800s. [13] By the turn of the century, the name was accepted for the particles in cathode rays.

1.1.2 Tolman and stewart

By the early 1900s, experiments had proven the electron to be the charge carrier in various liquid solutions. [3] This was proved in two different experiments. One experiment was done with tubes of liquids, with electrodes at both ends, spinning at high revolutions per minute. The electrons carried a negative charge to one end of the tube and the charge difference was measured by the electrodes.

Several similar acceleration based experiments were tried with metals, but with no success. Nichols, in 1916, rotated a disk of aluminum with contacts at the edge and at the center. [3] He was able to determine that the charge carrier had a mass less than that of hydrogen, however, he could not be more specific due to the significant amount of noise caused by the rubbing contacts at the edge.

Tolman and Stewart adopted Nichols's rotating experiment and improved upon it. Instead of a disk, they used a coil of wire. Instead of having contacts at the center and edge of the coil, they wrapped the coil in such a way that both contacts were at the center. This avoided the rubbing contact that introduced noise by creating one solid circuit. Rubbing contacts aren't solid and can interrupt the signal . The coil was then spun at several thousand revolutions per minute and suddenly stopped. This resulted in the electrons continuing to flow around the coil due to their inertia and ability to "flow" in metals. This created a small, but measurable current. From this current Tolman and Stewart calculated the charge to mass ratio. [7]

1.2 Charge to mass ratio

During the late 1800s, several experiments performed by J. J. Thompson [4] came close to estimating the charge, e, of cathode rays. He was one of the first people to estimate of the charge to mass ratio and estimated that the electron was 1000 times smaller than that of a hydrogen atom. He did this through experimenting with cathode rays, similar to Arthur Schuster. His experiments were crude and required Thompson to make estimations. This introduced a large amount of uncertainty into is data and prevented a more precise estimate of the ratio.

Today, the charge to mass ratio of an electron is well known, and plays a role in several theories and equations. This ratio is important in electrical conductivity, and therefore important in thermal conduction as well. The mass-to-charge ratio is widely used in optics, specifically in electron optics. Knowing the mass-to-charge ratio of an electron to a high degree of accuracy is what allows electron microscopes to be very precise.

1.3 Recreating the Tolman-Stewart experiment

1.3.1 Project origins

The idea to recreate the Tolman-Stewart experiment started with Judith Olson in Ithaca College's Advanced Physics Laboratory course in 2009. Olson started research on the Tolman-Stewart experiment with help from Dr. Rogers, and completed the majority of the theory. [5]

Olson's initial design greatly varied from the current design as several improvements have been made since the project's origins. Originally, the device used a belt attached to a motor to turn the copper coil. Later, a variable DC motor was substituted for the belt. The original experiment carried out by Tolman and Stewart had copper wires going from the coil, leading up to the ceiling, wrapping around a support on the ceiling, and attaching to a galvanometer on the floor. When the coil spun, the copper wiring twists. The long length of wire prevented it from breaking when it was twisted. Olson followed this in her recreation of the experiment. Unfortunately, the ceilings available in CNS are not high enough. When spun, the copper wires snapped spun around at high RPM.

After the Advanced Physics Laboratory course, Olson continued working on this project and made several modifications. Instead of the copper wires going to the ceiling, a mercury differential is used. A mercury differential has four main components. The bottom of is a metallic plug that can be attached to a circuit. On the top is a similar plug. Between these two plugs is a chamber full of mercury inside a metal casing. This setup allows the top plug to remain stationary while the casing and bottom plug spin with the Tolman-Stewart device. This allows for there still to be a completed circuit, without the dangers of the previous set up.

Alex Viola continued where Olson left off in the spring of 2012. At this time, the experiment lacked a successful brake. Alex began theorizing possible brakes. He came up with the idea of using a modified bike brake. [6] This is the brake that is currently being used.

1.4 Intermediate physics laboratory

PHYS-360000: Intermediate Physics Laboratory at Ithaca College is a class where physics majors learn how to properly preform a scientific experiment. The goals for this class are:

1. To further students' knowledge and abilities in error analysis, including: er-

ror propagation, mean and standard deviation, least squares fitting, weighted averages, normal distribution, chi-squared

2. To train students in data collection, analysis, and presentation (graphing) via MathWork's MATLAB

3. To teach students how to summarize experiments in project report format, including a basic understanding and explanation of the theoretical framework of the experiment,

4. To learn computerized data acquisition via MATLAB, where programs can be modified by the students

5. To teach students the importance of a laboratory notebook, and how to use it properly

6. To give students experience with a variety of different experiments in various physical phenomena, including canonical experiments, and

7. To train students to work independently with modern experimental equipment.

[11]

This experiment helps the students achieve each of the goals. The system has several variables all of which have varying degrees of uncertainty. The data collection is through modern measuring devices and requires MATLAB to graph.

The Tolman-Stewart experiment also has a large amount of theory involved due to the experiment being based on the properties of the unseen electrons. Students must visualize what the electrons are doing in order to understand how the experiment works.

The experiment also has a large number of steps involved. This encourages students to carefully understand the directions and theory before preforming the experiment. If students don't understand the theory, or rushed through the steps, they will certainty get bad data.

This is an ideal experiment for this course because it not only uses skills they should have learned in other classes, but it also forces them to preform an experiment carefully and properly.

1.5 Tolman-Stewart project

This thesis discusses how the Tolman-Stewart experiment has been recreated for Ithaca College's Intermediate Laboratory course. This includes the experiment's construction and design, as well as necessary safety precautions. It will include a detailed theory section relaying and updating the theory that Tolman and Stewart originally worked on.

Chapter 2

Theory

2.1 Conceptual theory

2.1.1 Movement of free electrons

In the early 1900s, scientists were debating how electricity was carried through metals. We know today that, in most metals, electrons are responsible. Inside of the metal, there is a metal lattice where the electrons are bound. They are no longer bound to a single atom and are considered "free electrons". [9] At room temperature, with no current applied, these electrons can randomly move around with zero net current. The speed of these random movements is called drift velocity.

2.1.2 Induced current

Initially, everything is at rest and the electrons have no outside force acting on them inside the copper coil. As soon as the coil begins to spin, the electrons begin to lag behind it. [7] This is caused by the electrons not being attached to the atoms, and being free to move. If the coil is accelerated fast enough, there can be a small negative current caused by the electrons appearing to flow backward.

After the coil is spinning at the desired speed, it is stopped very suddenly. This results in the electrons being flung forward by their momentum. They continue to spin around the coil, creating an induced current. The charge-to-mass ratio can be determined from the relationship between the induced current and the speed the coil was at before it was stopped.

2.2 Forces acting on the electron

Tolman and Stewart identify three forces acting on the electron inside of the copper coil. These forces are the electrical force, frictional force, and acceleration force. [7] We know more about these forces today than Tolman and Stewart did and can consequently modernize their equations for these forces. The original derivation can be found in appendix A.

2.3 Modern derivation

2.3.1 Deriving current

In this experiment, current flows through the circuit and is defined as

$$I = \frac{dQ}{dt} \tag{2.1}$$

We know that dQ/dt is change in charge over change in time and can rewrite dQ/dt as the number of charges per volume times the change in volume.

$$\frac{dQ}{dt} = ne^{-}A\frac{dl}{dt} \tag{2.2}$$

$$ne^{-}A\frac{dl}{dt} = ne^{-}AV \tag{2.3}$$

$$ne^{-}AV = ne^{-}AR\omega \tag{2.4}$$

Where R is the radius of the coil and r is the radius of the copper wire and n is the number of electrons per unit volume. dl/dt is just a velocity and because the coil is spinning, we must use angular velocity. Equation 2.4 does not take into consideration all of the electrons in the coil. To do that, we must introduce a new constant, N

$$N = n(\pi r^2)(2\pi R) \tag{2.5}$$

$$n = \frac{N}{(\pi r^2)(2\pi R)} \tag{2.6}$$

Plugging Equation 2.6 into 2.4 gets

$$I = \frac{Ne^{-}\omega}{2\pi} \tag{2.7}$$

2.3.2 Deriving kinetic energy

The electrons have a kinetic energy when they are moving around the coil. The electrons create a hoop around the center with an angular momentum of $L = MR^2$ where M is the total mass of the electrons.

$$E_{rot} = \frac{1}{2}Mr^2\omega^2 \tag{2.8}$$

The total mass of the electrons is $M = Nmp$ where m is the mass of the electron and p is the number of turns in the coil.

To find how the kinetic energy changes over time, we take the derivative of Eq 2.8

$$d(kE_{rot}) = Nmpr^2\omega d\omega \tag{2.9}$$

2.3.3 Joule heating

When the electrons are slowing down, they lose some Kinetic energy to Joule Heating. The amount of energy lost can be written as

$$H = I^2Rt \tag{2.10}$$

Taking the derivative of Eq **??** and solving for dQ, we find

$$\frac{dQ}{dt} = I^2RdQ = I^2Rdt = dE \tag{2.11}$$

2.3.4 Finding e^-/m

Setting Eq. 2.9 equal to Eq. 2.11 gets

$$I^2Rdt = Nmpr^2\omega d\omega \tag{2.12}$$

$$Idt = \frac{Nmpr^2\omega d\omega}{IR} \tag{2.13}$$

Dividing by IR gets Idt on the left hand side. This is important because the next step is plug Eq. 2.7 in for the I on the right side and simplify.

$$Idt = mpr^2\frac{2\pi}{e^-}d\omega \tag{2.14}$$

The integral of the left side should be recognized as Q, the total charge. Integrating both sides gets

$$q = \int Idt = \int_{\omega_0}^{0} \frac{2mpr^2\pi}{e^-R}d\omega = \frac{m}{e^-}\frac{2pr^2\pi}{R}(0-\omega_0) \tag{2.15}$$

Solving for $\frac{e^-}{m}$ here would get a correct equation, but during the creation of the current device, the number of turns, p, was not counted. We can substitute out the number of turns times the resistance of one turn, R_1p, for the total resistance, R

$$R_1p = R \tag{2.16}$$

Plugging 2.16 into 2.15 and simplifying gets

$$q = \frac{m}{e^-}\frac{2r^2\pi}{R_1}(\omega_0) \tag{2.17}$$

The minus sign on the ω_0 can be ignored because it just indicates a direction. Spinning the coil one way gives a positive charge, and spinning it the opposite direction gives a negative charge. This is expected and is considered in the design of the apparatus and circuit.

Solving 2.17 for $\frac{e^-}{m}$ finds the results in equation 2.18

$$\frac{e^-}{m} = \frac{2r^2\pi}{qR_1}(\omega_0) \tag{2.18}$$

Chapter 3

Methods

3.1 Experiment apparatus

3.1.1 Original design

The design Olsen and Dr. Rogers came up with varies from what the design is now. Originally, the coil was to be turned by a gear connected by a belt to a motor. The reasoning for this was to avoid any electrical interference a motor's magnetic field may cause on the copper coil. Figure 3.1 shows the original device. The belt is labeled B. [7]

Olsen and Rogers also copied Tolman and Stewart design in that wires came from the top of the coil and were attached to the measuring device, represented by G in figure 3.1. This worked for Tolman and Stewart because they had sufficiently high enough ceilings. The ceilings in Ithaca College's Intermediate Physics Laboratory have been found to be too low. When the coil was spun, the wires coming from the top were also spun. With high ceilings, there was a low chance of the wires spinning too much and breaking. Unfortunately, Olsen didn't have access to high ceilings resulting in a high chance the wires would snap, ruining the experiment.

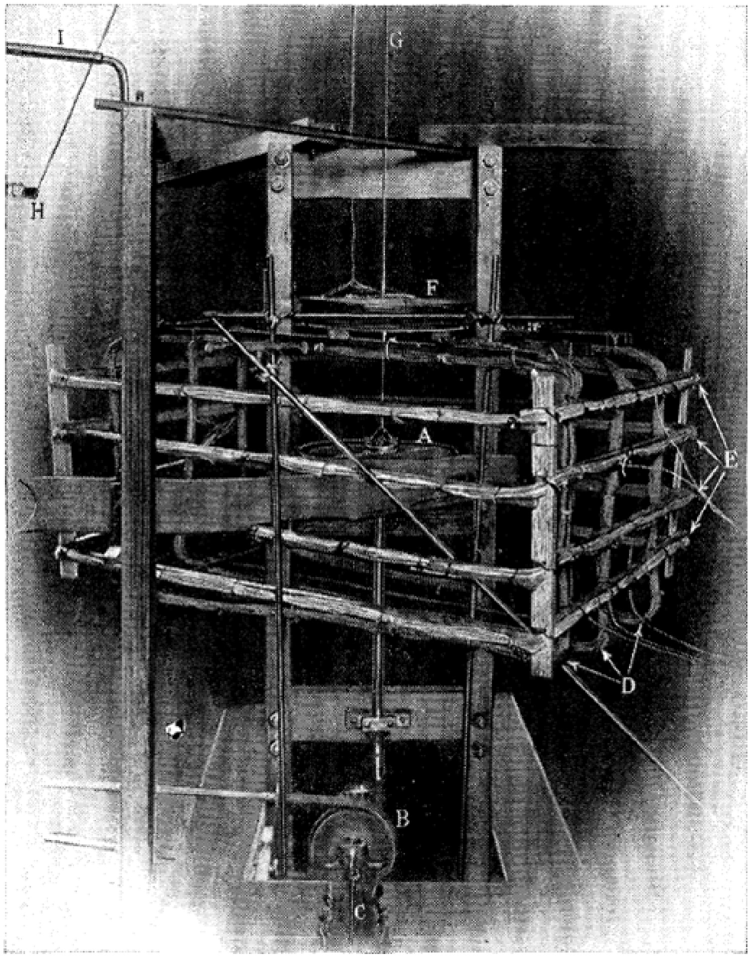

Figure 3.1 This is the original device created by Tolman and Stewart in the early 1900's. It consists of a large copper coil (A), being belt driven (B) by a motor not shown. The device is stopped by a large leather strap seen near A and the signal runs up cables (G) to a measuring device not shown. [7].

The braking mechanism for the original design used a large leather strap that tightens on the coil bringing it to a stop. Olsen also included this into her original design.

Olsen's design varied from Tolman and Stewart's in that she did not include the cage of coil, D and E, around the device. Tolman and Stewart used the cage and compensating coil to cancel out any influence the Earth's magnetic field may have on the coil. Olsen designed a smaller, more compact support for the coil and the shaft.

Although it has been slightly modified, the support is still used.

To measure the angular velocity of the coil, Tolman and Stewart used a magneto, an electric generator. They found that 1 centivolt = 0.726 rev per second [7] and knew how fast the coil was going by the voltage coming out of the magneto. Olsen realized this method is outdated and substituted in a common photogate to measure the angular velocity.

3.1.2 Design modifications

After Olsen graduated, the project went through several modifications by a few different people. The first and most prominent issue was the wires breaking after being twisted too many times. Suggested fixes for this included metal brushes that would make electrical contact with the coil. This would have been ineffective because friction contacts introduce additional noise, and is in fact why experiments before Tolman and Stewart's failed. Emily Backus (Ithaca College Physics '12) fixed this issue by substituting the wires going to ceiling with a mercury slip ring, which allowed for a constant electrical connection where one end spins and the other remains still.

The belt driven shaft was found to be unreliable. The belt would slip or fall off. A DC motor was installed with the drive shaft of the motor connected directly to the shaft spinning the coil. Although this fixed one issue, it introduced several new ones. One issue was that the motor was incredibly powerful and if plugged into an outlet spun the coil to terrific speeds far too quickly. A variable power supply was used instead of the outlet to fix this issue.

After these issues were fixed, the next major issue was the brake. The leather strap that was originally used proved difficult to emulate. There was no reliable way of using the strap to get the coil to stop fast enough and required the user to use their strength to stop the coil. Alex Viola (Ithaca College Physics '13) came up with the idea of using a bike brake attached the coil/shaft support.

Figure 3.2 Alex Viola and Julia Russ made several modifications to the device. A new middle plate was made that was able to have a bike brake mounted to it. The mercury slip ring is the black piece on the top of the device.

3.2 Design improvements

3.2.1 Improving the braking mechanism

The project was passed from Viola to myself before he had a chance to install the bike brake. Soon after it was installed however, it became clear that a normal brake didn't have the stopping power that was required. The brake had to be able to stop the coil spinning at 5000 RPM in a fraction of a second. There were two main issues with the brake: the brake pads were designed for a mostly flat surface and the brake handle didn't allow the use to impart much force to the pads. A new handle and new pads needed to be designed. The handle was fairly simple to redesign. By extending the lever, the user could pull much harder on the cable than with the previous design. Bike brake pads are made of a rubber specifically made for bikes. They are made out of a hard, low tear, rubber. This makes them great for stopping a bike but the rubber slides too much along the shaft. The first modification was to make the brakes rounded. This allowed for more contact, with slight improvement in the stopping time. This led to redesigning the brake pads entirely, using a new form of rubber. Rubber comes in many different forms for many different uses. For this experiment, we looked at hard and soft rubber. Soft rubber "grabs" onto things and has a very high coefficient, but is much more susceptible to tearing. Hard rubber has a higher chance of sliding when coming into contact with something, but is much more tear resistant. Two forms of rubber were tested: medium soft and medium hard. They were chosen because they were most likely to have a good combination of high friction and low tearing. At lower RPMs, the softer rubber stops the shaft faster. However, at a RPM above 3500, the soft rubber tears and the hard rubber stops the shaft faster. The brake pads themselves were made by milling a 1' hole through a 2' x 2' x 1' cube of rubber, then cutting the cube in half creating two pads. An aluminum plate was screwed onto the back of the pads. This plate was then attached to the prongs of the bike brake, as seen below.

3.2.2 Safety Improvements

Up until this point, the device was relatively dangerous. The coil spins at 5000 RPMs, meaning the outside edge is moving at over 100 mph. To ensure the safety of the experimenter, Jennifer Mellot (Ithaca College Physics Department) built an aluminum box to contain the device, seen in figure 3.3

The aluminum box does more than just protect the user however. One of the mercury slip ring needs to be held in place. It is attached to the top of the aluminum box via being glued to a rod that is then screwed into the top of the box. The aluminum box also proves to be very efficient at shielding the coil from any outside electric interference. Although Olsen found Tolman and Stewart's cage to be unnecessary, the coil still needs to be shielded from all electrical interference. This is evident in the large amount of noise in the data. This helps in reducing noise, which can be significant compared to the signal size of tens of nanocoulombs.

3.2.3 Noise reduction

Early testing showed that while the motor was spinning, even spinning down, it created an immense amount of noise, completely covering the signal. The graph below is an example of the significant amount of noise the motor creates.

There are a few different ways to fix this problem. Tolman and Stewart solved it by moving the motor away from the coil. This was tried by Olsen originally and did not work. Another way to fix the issue is to surround the motor in mu metal. This would channel the magnetic fields, coming from the motor, away from the coil. This

Figure 3.3 As a safety precaution, an aluminum box was made to surround the device in case anything came off while spinning at high speeds and would protect the experimenter from flying debris. It also proved to be helpful in reducing electromagnetic noise. The door is made of a durable plastic and is see through in order to measure the RPM of the device.

solution dramatically reduced the noise coming from the motor.

With the noise from the motor covered, it became clear that the signal is still very small, too small to discern from the noise. An amplifying circuit was suggested. The circuit would filter out some of the noise and increase the size of the signal.

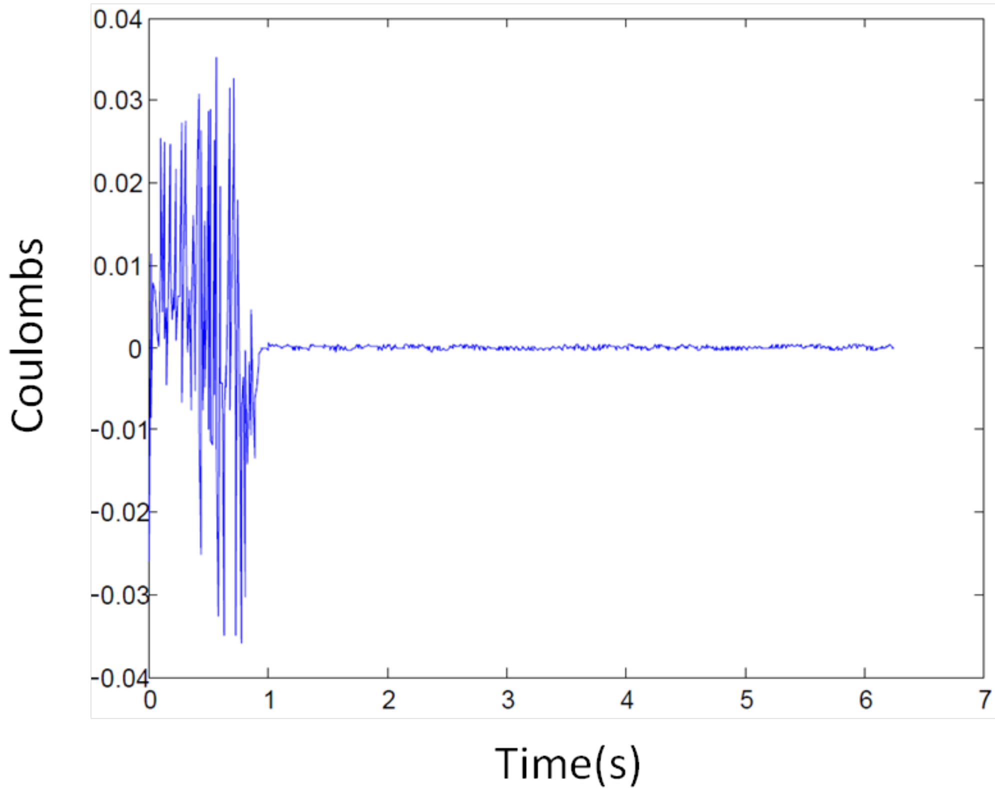

Figure 3.4 This is a graph of the output signal of the device very early on. From 0 to just before 1 second the device is spinning at 5000 RPM and then stopped. The signal dies very quickly to background noise. The expected signal is on the order of nanocoulombs and is being covered up by the large amount of noise.

3.2.4 Amplifying Circuit

The circuit consists of two OP-Amps which amplify the signal. Figure 3.5 shows a schematic of the circuit. The voltage supply (VG1), 100M resistor and ammeter (AM1) aren't part of the actual circuit but are used in the program TINAv9.3 by Design Soft to simulate a very small current. The circuit was designed and tested in a program called TIA before being fabricated.

TINA allows the user to test the expected signal at various parts of the circuit. Figure 3.6 shows the signal going in at 20 nA at AM1. The half of the circuit turns the signal into 2 mV and the second half increases it to 200mV.

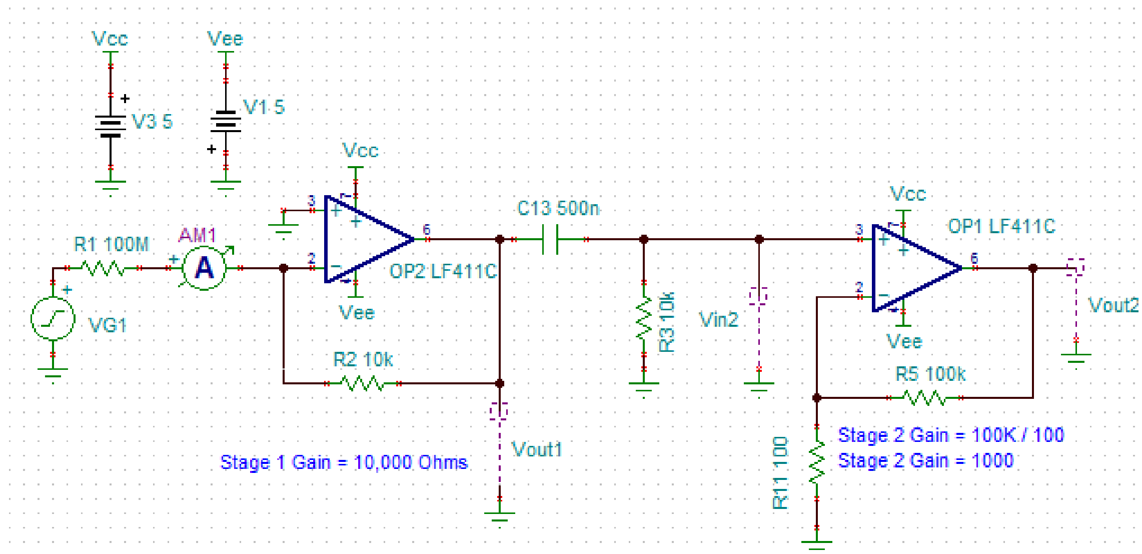

Figure 3.5 This is a schematic of the circuit used to amplify the signal and reduce noise. The voltage supply (VG1), 100M resistor, and the ammeter (AM1) aren't part of the actual circuit. They are in this diagram to simulate an input signal of 20 nA. The

This greatly increases the chances of recording a signal. The large amplification means that the output signal will be much larger than any noise that may interfere between the circuit and the measuring device.

3.3 Recording data

3.3.1 Data measuring devices

This experiment requires measurements to be made very quickly and is therefore impossible to do it by hand. An electrometer, which is sensitive down to the nanocoulomb range, can do this. The electrometer can only store a limited number of data points which requires the user to start recording data within a few seconds of stopping the brake. This can be simplified by using a computer.

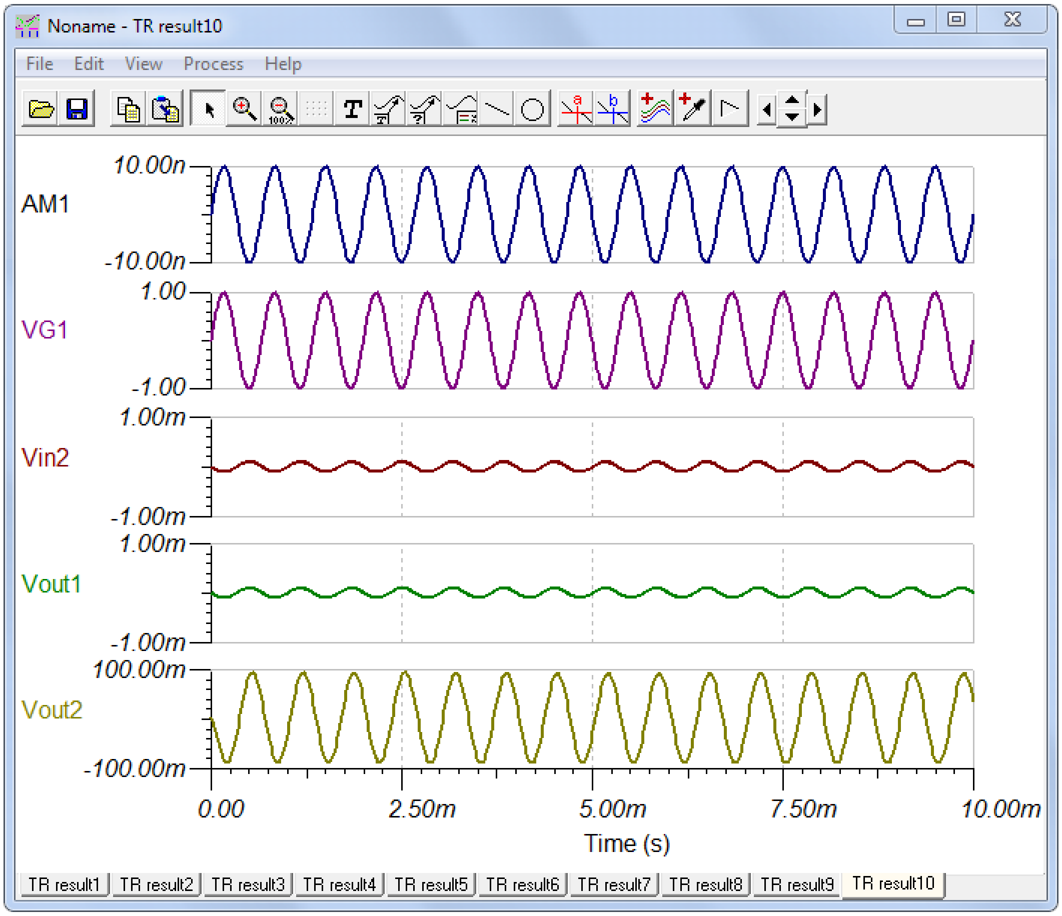

Figure 3.6 The program TINAv9.3 by Design Soft allows the user to see the signal strength at various points throughout the circuit. This figure shows the expected signal strength and type of this circuit. The circuit should take an input of 20nA (AM1) and create an output of 200 mV (Vout2).

3.3.2 Measurement automation

The data collection is automated to make it simpler for future students. There are several things taking place simultaneously when recording data. First, the coil must be spinning at 5000 RPM. To measure the RPMs, a tachometer is used and aimed at a reflective tape on the shaft. Once the coil is spinning fast enough, the user must then run a program on National Instrument's LabVIEW. This program tells the electrometer to begin making measurements. The electrometer only has enough memory to make measurements for 8 seconds. In this 8 seconds the user must turn off the power to the motor, and then apply the brake.

Chapter 4

Analysis

4.1 Results and data

4.1.1 Using the collected data

The collected data is automatically saved as a .txt file. The file then has to be manually uploaded into mATLAB. One issue with this method is that the electrometer only saves a certain number of characters of data. This leads to the final datum point in mATLAB being unusable and must be manually deleted. Once this has been completed, the data can be plotted, using the command: $plot(name(2:3:end))$. This plots the data against the number of data points collected. The time interval over which this data is collected is set by the user at the start. For figure4.1, the data was taken over 8 seconds.

As previously stated, during the 8 second time window, several things must occur. The recording on the electrometer must be turned on, zero-check on the electrometer must be turned off, the motor must be turned off and then the coil must be stopped. Figure 4.1 shows all of these actions. When the value is exactly zero with no noise, the zero-check is on. This is from A to B. It is then turned off, B to C, and the value

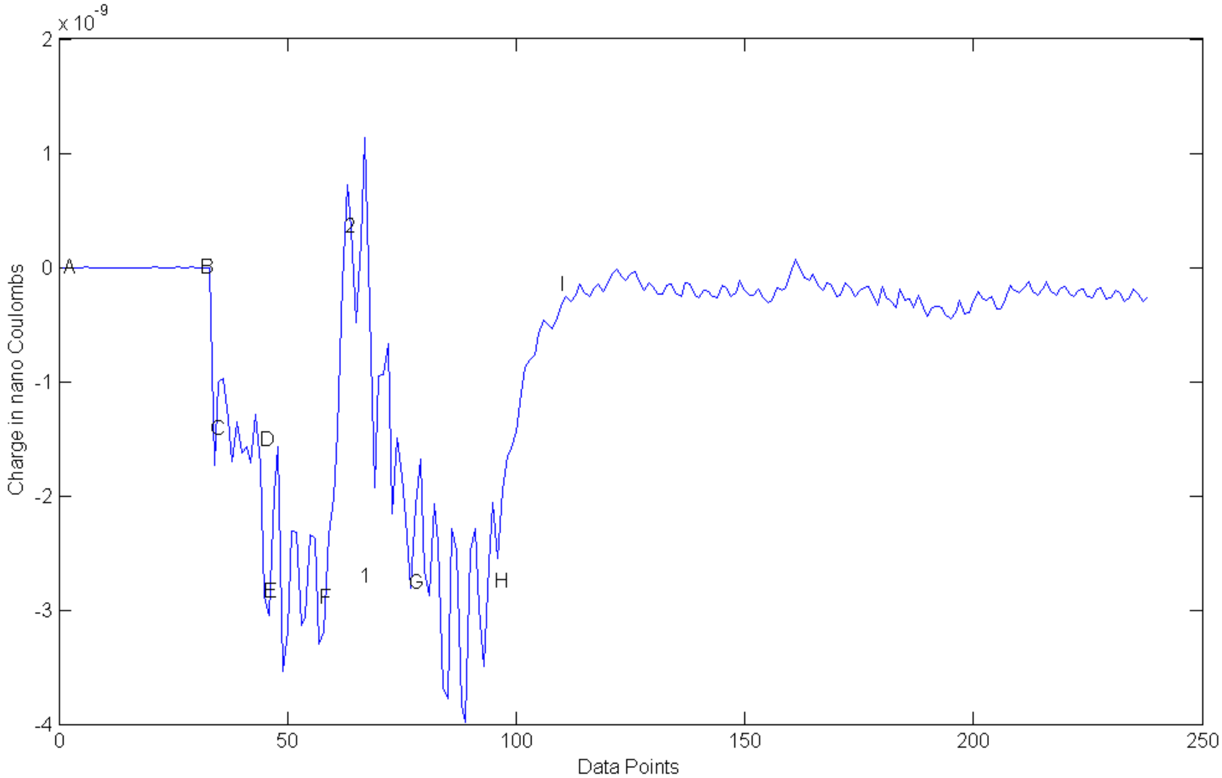

Figure 4.1 This graph shows the data collected after creating the circuit and using an electrometer. From A to B the electrometer had its zero check on, which makes the data read 0. From B to C, the zero check is turned off and from C to D the device is spinning at 5000 RPM with the power source on. At D, the power source is turned to 0, dropping the charge to E. At F the device is stopped, creating the spike in between F and G. From G to H the noise returns to levels caused only by the power supply. At H the power supply is turned off, and the charge dissipates to 0.

shoots negative and is constant with noise, C to D. The motor is then turned to zero causing the graph to go from D to E until the coil is stopped causing the spike in charge between E and G. The charge is only there for a fraction of a second before the system reverts back to the value before, G. From G to H, the value is negative because, although the variable power supply to the motor is turned to zero, it is not off. This causes some small charges to make the value negative. When the motor is unplugged from the power supply, the value goes from H to I and remains there with normal background noise.

Careful recording of the steps taken during the 8 seconds is key. The experiment would have worked if the motor was unplugged instead of turning the power supply to zero. The reason I preformed the steps I did was because with one person it is easier to turn the power supply to zero as well as the graph is easier to interpret. Unplugging the motor would have caused the charge to naturally increase toward zero. If the coil was stopped before the charged reached zero then a larger than actual spike would have appeared on the graph.

This graph proves that a signal is sent from the coil, through the circuit, to the measuring device. However, one graph is not enough data to say whether or not the device works. More data will have to be collected in order to determine how accurate the measurements are. Due to unforeseen technical difficulties, it was not possible to collect additional graphs at this time.

4.1.2 Uncertainty

Uncertainty comes from a few different parts of the experiment. There is electromagnetic interference with the coil from outside sources, like the motor. This affects the size of the spike in conjunction with human error in measuring it. Part of the future work will be to reduce the impact of this noise. The circuit, currently attached to the outside of the aluminum box, will need shielding around it as well, to prevent electromagnetic interference. There is also some uncertainty in the speed of the coil. The tachometer makes a measurement once per second. During that second it is possible for the coil's speed to fluctuate as much as 200 RPMs if the coil has not reached a stable speed. Once the coil's speed has leveled off, it is still possible for it to change as much as 30RPMs within that second time frame. The radius of the coil has some small uncertainty associated with it due to human error in measuring it. The resistance of the coil has relatively high uncertainty as it was measured using an ohm meter that was not very precise.

4.2 Experiment

4.2.1 Suitable experiment for intermediate physics laboratory

Experiments in Intermediate Physics Laboratory normally have a procedure that accompanies it that explains how the experiment works. It is then the job of the experimenter to figure out the correct way to preform the experiment to collect useful data. The Tolman-Stewart experiment follows that pattern. A procedure explaining the experiment can easily be written without giving away too much of the experiment. It will then be the job of the experimenter to calculate how fast the device needs to be spinning to collect useful data. The theory leading up to this calculation requires an understanding of calculus which third year physics students should have. This experiment also requires the students to understand finding error and error propagation. These skills are taught during the first few weeks of the course and the Tolman-Stewart experiment is a perfect way of practicing those skills.

Students in Intermediate Physics Laboratory predominately work in pairs. This experiment is very well suited for pairs due to the timing issues involved. It is much easier for two people, working together, to record RPMs, begin measuring data, turn off the motor, and then stop the device all within 8 seconds than it is for one person.

4.3 Conclusion

4.3.1 Safety

The experiment has proved to be very safe by having a low probability of something breaking combined with a high probability the aluminum box will contain any flying debris. The few times in which a loose nut came off was a result of not checking it for an extended period of runs, more than 10. In the procedure for the device an additional step to check the tightness of each nut and bolt before every run will be included. The loose nut was by far the most common item to come off the device. In earlier testing, wire or tape came off at high RPMs. There is still tape on the device that could come off and this may need to be addressed before the experiment is implemented in intermediate laboratory.

The experiment does not require the device to be spinning faster than 5000 RPMs but it is capable of going much faster. The highest RPMs the device can go before becoming unstable is 7000 to 8000 RPMs. The device becomes unstable by vibrating violently which dramatically increases the chances of either a nut coming loose or causing physical damage to the device. Going above 6000 RPMs also reduces the efficiency of the mercury slip ring and will ruin any data collected at those speeds.

4.3.2 Future Work

This project has several things that must be done before it is completed. The shielding needs to be completed. This includes an aluminum door for the box, shielding around the circuit and improved shielding around the motor. Throughout the course of this project, the programs used have had to switch from various computers and, as a result, no longer work with the current version on the available computer. Also as a result of extensive testing, the brake pads might have worn down too much to be effective at stopping the coil in time.

4.3.3 Intermediate physics laboratory worthy

After running the experiment hundreds of times, the chances of injury are minimal. Out of those runs, less than 10 of them had something come loose and none of those items got past the aluminum box. If the experimenter is responsible and checks the tightness of the nuts then the experiment becomes even safer. This experiment is a perfect education tool for the Intermediate Physics Laboratory course. It fits the model of what the class is trying to teach and utilizes skills the students learned either in the course or in previous courses. It also challenges them with a semi-difficult procedure that requires careful attention to steps and good note taking.

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Appendix A

Theory derived by Tolman and Stewart

A.0.4 Electrical force

The electrical force comes from there being an electrical potential between the two ends of the wire. If V is the electrical potential, the potential gradient at any point will be

$$V/l \tag{A.1}$$

where l is the length of the wire. Using equation 1.1, Tolman and Stewart find the force acting on a mole of electrons to be

$$F_e = VQ/l \tag{A.2}$$

Where F_e is the electrical force and Q is the Faraday constant, or $96,485C/mol$.

A.0.5 Frictional force

What Tolman and Stewart call the frictional force occurs when the metal begins to accelerate. Because the electrons are free to move inside of a copper wire, the electrons lag behind the accelerating copper atoms. Tolman and Stewart [7] state that if U is the mobility of an electron, the velocity it attains under a unit gradient, the frictional force is

$$F_f = vQ/U \tag{A.3}$$

Where v is the difference in velocity between the metal and the electrons.

A.0.6 Acceleration force

Tolman and Stewart are very vague about what the acceleration force is. This is due them not understanding what is happening to the electrons on an atomic scale. They simplify this force and state that the acceleration force is

$$F_a = ka \tag{A.4}$$

k is a constant whose values starts unknown and a is the acceleration of the metal.

Tolman and Stewart continue with this derivation, eventually getting an equation for the total electricity that passes through the circuit. Showing this derivation is unnecessary due to a simpler and more modern derivation.