Implementation of Charged Conducting Spheres Fabricated Using Carbon Conductive Paint and Used in Conjunction with a Torsion Balance to Analyze the Relationship Between Coulombic Force and Distance

Lizzie Apel

(Dated: May 1, 2019)

Understanding the effect that electrostatic or Coulombic force has on charged spheres in relationship to the spheres' separation distance is of import. Practical applications of this theory include the cases of ink jet printing, spray atomization, cloud formation, and fuel injection [1]. The simple inverse square relationship between Coulombic force and distance between two geometrically identical charged spheres is examined in this article. Using a Coulomb torsion balance apparatus, data was analyzed comparing the properties and behavior of the original conductive spheres provided with the apparatus by the manufacturer versus a new set of conductive spheres. These spheres were engineered and fabricated by experimenters using ping pong balls and carbon conductive paint, a substance with applications in electromagnetic shielding [2] and marine biology [3]. Data fitting for the painted spheres yields a vacuum permittivity constant ϵ_0 of 6.09×10^{-12} Farads per meter $\pm$ 6.11×10^{-13} Farads per meter, agreeing within 4 uncertainties with the accepted ϵ_0 value of 8.85×10^{-12} Farads per meter [4]. Ping pong balls painted with carbon conductive paint thus appears to be a promising and viable option for constructing and engineering conductive spheres for use in classroom torsion balance experiments, worthy of further consideration. Challenges faced and ways to improve this technique are discussed within.

1. INTRODUCTION

Electrostatic force, also known as Coulombic force, is defined as the attractive or repulsive force between stationary charges or charged objects [5]. Study of the concept of electrostatic force as it relates to spherical geometry lends itself to greater understanding of the behavior of and interactions between charged spherical particles, such as those involved in cloud formation, fuel injection, and ink-jet printing [1]. The study of electrostatics in practical settings is aided by the advent of conductive coatings or paints [2], one use of which (to facilitate static charge dissipation and redistribution) is documented in this report. Other modern applications of electrically conductive paints or coatings incorporating graphite and carbon black include uses in electromagnetic and radio frequency interference shielding [2], as well as in electrochemical disinfection treatments on fishing nets in an effort to curb marine biofouling [3], and in the production and engineering of conductive paper [6].

Coulombic force is the governing scientific effect which dictates how two charged objects will behave in interactions with each other. This relationship is distance-dependent, meaning that the Coulombic force between two charged objects varies with the distance between them. The experiment detailed in this article utilizes two conducting spheres of identical size and geometry, specially hand fabricated in the lab environment using ping pong balls treated with a carbon conductive paint. The two spheres are charged to the same potential and subsequently used in conjunction with a torsion balance to examine the relationship between Coulombic force and distance. This allows for assessment of the performance, practical effectiveness, and scientific integrity of the method and materials used to create the conductive spheres. In order to assess the Coulombic force between the two spheres over varying distances between the spheres' centers, one sphere was suspended vertically within the torsion balance and allowed to freely rotate horizontally about a torsion wire, whilst the other sphere was mounted on a sliding scale. The degree to which the Coulombic force between the two spheres caused the torsion wire to twist is directly proportional to the force's magnitude [4]. Data was taken with both the original spheres provided by the manufacturer and the painted spheres created in the lab for comparison purposes alongside previous data taken with the original spheres earlier this semester for Lab 3.

2. BACKGROUND AND THEORY

2.1. Coulombic Force

In the case of two point charges, there exists a simple inverse square relationship between the resulting Coulombic force and the separation distance of the charges [7]. This relationship is given by Coulomb's Law, which is defined by the following equation [4]:

$$F = \frac{kq_1q_2}{R^2} \tag{1}$$

Where F represents the magnitude of the Coulombic force in Newtons, k represents the Coulombic constant 9×10^9 in N^2m^2/C^2 [4], q_1 and q_2 represent the respective charges in Coulombs, and R represents the distance between the two charges in meters.

2.2. Coulombic Force Between Two Spheres

This simple inverse square relationship, while valid for the case of two point charges, necessitates some modification before it can be useful in applications involving two spheres, due to the reality of charge redistribution over a spherical surface [7]. For large distances between spheres, the simple inverse square relationship is a reasonable model, as an electrostatically isolated charged conducting sphere can be modelled as a point charge, given that the charge will distribute evenly over the sphere's surface such that the center of the sphere is in fact the center of the charge distribution [4], [1]. In the case of sphere separation distances that are small relative to the size of the spheres, however, the inverse square relationship will not hold true [4], [8]. This is due to the fact that bringing the spheres close together compromises the electrostatic isolation assumption crucial to successful modelling of the spheres as point charges- instead of the charge distributing evenly over the surface of each sphere, the two charges will instead interact, distributing over the spheres so as to minimize the electrostatic energy [4]. For small distances between sphere centers, the Coulombic force between two charged spheres is subsequently less than the inverse square model would predict for two point charges [4].

2.3. Correction Factor

For analysis of data collected using their Model ES-9070 Coulomb Balance apparatus and the two included geometrically identical spheres, PASCO Scientific has provided a correction factor by which to multiply dependent variable values. In analysis of data taken using the spheres fabricated specifically for this experiment, this correction factor is applied in order to correct the deviation from the point charge inverse square model observed in the case of small distances, due to the differences outlined above in charge distribution that stem from spherical geometry. PASCO Scientific suggests that each recorded value for torsion angle be multiplied by the inverse of the correction factor B as follows [4]:

$$B = 1 - 4\frac{a^3}{R^3} \tag{2}$$

Where a represents the sphere radius in meters and R represents the distance between sphere centers, also in meters.

PASCO Scientific does not provide a derivation for this correction factor. However, in an incredibly lengthy derivation performed by Slisko and Brito-Orta based on the method of electrical images and the theory of Larson and Goss as well as Maxwell's zonal harmonics, a similar formula for correction was reached, whose first and most significant term is expressed as follows [7]:

$$F_c = \frac{q^2}{4\pi\epsilon_0 R^2} \tag{3}$$

$$F' = F_c(1 - 4B^3) \tag{4}$$

Where F_c represents an expression in Newtons for Coulombic force derived from the formula for the capacitance of an isolated conducting sphere [4], q represents the sphere charge in Coulombs, ϵ_0 represents the vacuum permittivity constant 8.85×10^{-12} Farads per meter [4], R represents the distance between sphere centers in meters, F' represents the corrected value for Coulomb force in Newtons, and B represents the sphere radius in meters divided by the sphere separation distance in meters.

2.4. Measuring Charge and Capacitance Using a Faraday Ice Pail

A formula for the capacitance C in Farads of an isolated conductive sphere is given by the following equation [4]:

$$C = 4\pi\epsilon_0 a \tag{5}$$

Where a equals the sphere radius in meters and ϵ_0 represents the vacuum permittivity constant 8.85×10^{-12} Farads per meter [4].

Additionally, the following expressions relate the charge q in Coulombs of each sphere to the capacitance equation C of each isolated charged conducting sphere and the voltage V of 6000 V $\pm$ 50 V used to charge the spheres [4]:

$$q = CV \tag{6}$$

$$q = 4\pi\epsilon_0 aV \tag{7}$$

In this experiment, the charge on the painted spheres was measured directly using an electrometer, a capacitance meter, and a Faraday ice pail. As the combined capacitance of the ice pail, electrometer, and connecting leads greatly exceeds the capacitance of the conductive sphere, if a charged sphere is lowered by a thread into the central pail of the Faraday ice pail and then touched against its metal side, the sphere's charge will transfer to the pail and be subsequently measured and reported by the connected electrometer [4]. A PASCO Scientific

Basic Electrometer Model ES-9078 on the 100 Volts Full Scale setting was connected to a PASCO Scientific Faraday Ice Pail Model ES 9042-A following instructions provided by PASCO Scientific [4], and an ESCORT ELC-120 LCR Capacitance meter on the 200 pF setting was then used to obtain a combined capacitance value C of 142.5 $\pm$ 0.3 pF for the ice pail, electrometer, and connecting leads, with uncertainty sourced from observed fluctuation of digital meter reading.

Five measurements were then taken of the electrometer's voltage reading upon a painted sphere being dangled on a thread into the central pail of the Faraday ice pail and touched to the pail walls. Prior to each measurement, the sphere and pail were grounded with a grounding probe, the electrometer was zeroed, and the sphere was then charged to a potential of 3 kV $\pm$ 0.05 kV using the PASCO Scientific Model SF-9586 Kilovolt Power Supply by holding the charging probe to the sphere's surface for one second. The instrument precision uncertainty of the electrometer was estimated to equal $\pm$ 1 V due to experimenter ability to accurately read the analog dial on the apparatus. The average electrometer voltage reading V obtained from these five measurements was 42.0 V $\pm$ 2.0 V.

2.5. Torsion Balance

In the experiment detailed in this article, a PASCO Scientific Model ES-9070 Coulomb Balance was used in conjunction with a PASCO Scientific Model SF-9586 Kilovolt Power Supply. The Model ES-9070 Coulomb Balance apparatus is an example of a torsion balance, a device often used to examine the magnitude of forces between charged objects [4]. The torsion balance assembly of the apparatus features a conducting sphere mounted on a counterbalancing rod and suspended vertically along a thin wire known as the torsion wire. The torsion balance assembly is then paired with a sliding scale assembly featuring a second, geometrically identical, conducting sphere mounted to a clamp that is free to move back and forth along a slide scale in order to set different distances between the two spheres. When good vertical and horizontal alignment of the two spheres is ensured, the suspended sphere is placed in its equilibrium position, the sliding sphere is placed at the desired distance from the suspended sphere, and both spheres are then charged using the power supply and an affixed charging probe, an electrostatic force is generated between the two spheres which will cause the suspended sphere to twist horizontally about its torsion wire. By reading the torsion angle dial on the torsion balance assembly, it is possible to measure the angle by which the torsion wire must be twisted to return the suspended sphere to its equilibrium position. As this angle is equivalent to the angle the torsion wire twisted in response to the electrostatic force, this torsion angle is representative of the Coulombic force between the two spheres [4].

In the case of this specific torsion balance, a simple manufacturer-provided equation exists relating the Coulombic force F in Newtons, to the recorded torsion angle θ in degrees, and a constant K in Newtons per degree for the torsion wire, which was obtained following basic calibration instructions provided by PASCO Scientific to equal 1.51474×10^{-6} Newtons per degree $\pm$ 4.76115×10^{-8} [4] [9]:

$$F = K\theta \tag{8}$$

By combining this equation with equations (1) and (6), assuming q_1 and q_2 to be equal, rearranging to bring θ to the left side of the equation, and then incorporating the small-distances correction factor provided by PASCO Scientific detailed in equation (2), the following final expression is formulated relating torsion angle of the suspended sphere to the distance between sphere centers [4]:

$$\theta = \frac{4C^2V^2}{K\pi\epsilon_0}\frac{1}{R^2}(1-4\frac{a^3}{R^3}) \tag{9}$$

2.6. Fabrication of New Conductive Spheres Using Conductive Paint

In accordance with suggestions found in scientific literature concerning the engineering and design of conductive spheres for apparatuses and experiments used to replicate, investigate, or verify Coulomb's original findings [10], ping pong balls and thin hollow plastic tubes sourced from commercially purchased cotton swabs were used as the structural basis for the conductive spheres and their mounting stalks. These materials were chosen due to their lightweight nature, hollow geometry, compatible size with the torsion balance apparatus, and insulating properties. The conductive paint used to treat the surface of the ping pong balls in an effort to create an effective conductive sphere was MG Total Ground Carbon Conductive Paint, applied to the surface of the balls in a single layer with a cotton swab, as suggested by other customers who have purchased this paint. Conductive paint generally consists of graphite or a similarly low-resistance metallic compound in pigment form suspended in a fluid binder, often epoxy polymer [2]. In some conductive paints, carbon black serves as an additional added pigment to further minimize resistivity [2].

3. METHODS AND PROCEDURES

Due to the tendency of static charges to redistribute and dissipate, several measures were taken prior to data collection to ensure minimum external interference with the charging process of the spheres. On days when data was taken, experimenters dressed in short sleeved cotton shirts so as to minimize any interference of static electricity carried on clothing while performing the experiment. Additionally, as it is difficult to maintain static charges in humid conditions due to surface conductivity [4], the data from Lab 3 earlier this semester that is used in the data analysis section of this report for comparative purposes was collected on days in which the humidity was relatively low, taken here to mean below 30 percent. Humidity was assessed using the laboratory's humidity meter, and recorded as being 10 percent on the first day of Lab 3 data collection and 26 percent on the second day. Data collected during the final lab period using both the newly manufactured painted spheres and the original spheres was collected on a day with 31 percent humidity. As the torsion wire is very delicate and its suspended sphere can move easily in response to air currents, care was taken to ensure there were no air drafts near the apparatus during the experiment by closing doors and windows. Other measures taken to isolate the spheres and their charges as much as possible include conducting the experiment on an insulating table, handling the spheres and their support rods as little as possible so as to avoid charge leakage, grounding and recharging both spheres before each individual measurement, and always holding the charging probe at the far end while charging the spheres so as to maximize distance between each sphere and the experimenter's hand, thus reducing the capacitive effect on the sphere by preserving its relative electrostatic isolation [4]. Each measurement was also recorded as quickly as possible after charging the spheres, in an effort to minimize the effect of inevitable charge leakage.

A figure detailing the steps taken in the creation of the new painted conductive spheres is included below in Figure 1.

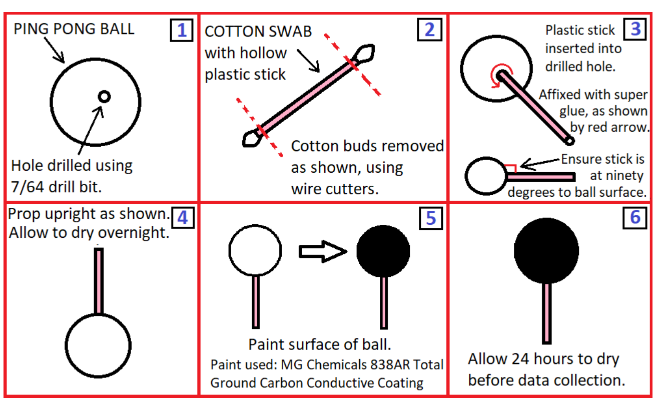

FIG. 1: Figure detailing the fabrication process used to engineer painted conductive spheres.

The original spheres have a radius of 0.019 meters as provided by PASCO Scientific [4], however the radius for the painted spheres had to be measured prior to the drilling and painting process. A set of calipers with a precision of $\pm\ 2{\times}10^{-5}$ meters was used to take three measurements of the diameter of the ping pong balls, which were then averaged. This diameter average was then halved to yield a radius result of 0.0189 meters $\pm$ $2{\times}10^{-5}$ meters. Spheres were wiped down with paper towels dipped in 99 percent isopropyl rubbing alcohol prior to painting in order to remove dust and surface oils from handling and prepare for optimum paint adhesion. During the painting process, spheres were held by their mounting stalks so as to not smudge the drying paint.

Prior to data collection with each set of spheres, the apparatus was assembled, calibrated, and its alignment was assured in accordance with the steps outlined in the instructional assembly video provided by PASCO Scientific [9], paying attention in particular to the horizontal and vertical alignment of the suspended sphere and the sliding sphere relative to each other's centers. In this initial calibration step, the apparatus was also turned on its side and adjusted using a set of small, manufacturer-provided microgram masses in order to obtain a value for the torsion wire constant K of $1.51474{\times}10^{-6}$ Newtons per degree $\pm\ 4.76115{\times}10^{-8}$. When the apparatus is properly calibrated, the suspended sphere and the sliding sphere should be aligned along their central axes, and the sliding scale should read 3.8 cm when the sliding sphere is positioned so as to just barely bring the two spheres in contact with each other, as this factors in both the manufacturer-provided sphere radius and the very similar radius of the painted spheres, then allowing the sliding scale to read out R as the distance between the centers of the two spheres.

An apparatus schematic of the slide scale assembly, torsion balance assembly, and power supply is included below in Figure 2. A closer examination of the torsion balance portion of the apparatus is included in Figure 3, with an additional side view of the torsion balance depicted in Figure 4.

It is of note that while collecting data using the original spheres, three clip on copper rings were used on the counterbalance vane for proper alignment, weight distribution, and levelling, whereas while using the painted spheres, no copper rings were needed in order to properly balance the suspended sphere assembly.

For each data point, as much distance as possible was put between the two spheres by moving the sliding sphere back to the far end of the scale. The torsion balance dial was then set to zero degrees, zeroing the torsion balance and returning the suspended sphere to its equilibrium position. Both spheres were then grounded using the power supply's attached grounding probe. Then the power supply was turned on and both spheres were charged using the charging probe, held at the far end of the probe- first the suspended sphere, then the sliding sphere. Both spheres were charged to 6000 Volts. Immediately after charging both spheres, the power supply was turned off. This technique helps minimize the effect

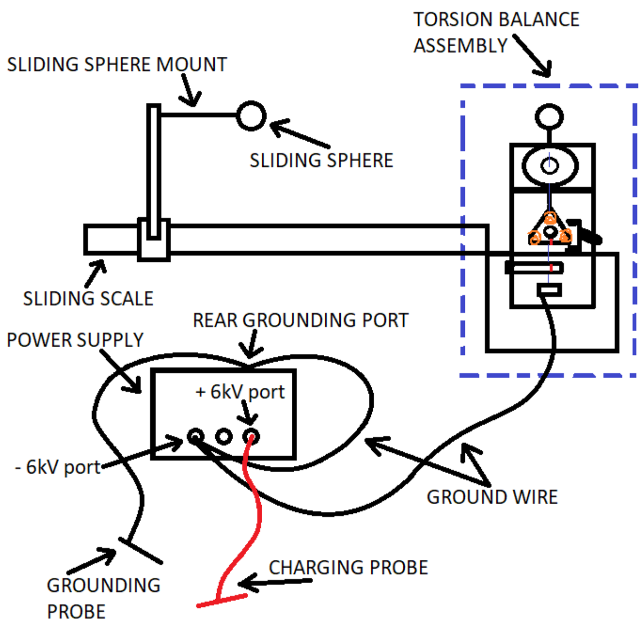

FIG. 2: Apparatus schematic detailing the PASCO Scientific Model ES-9070 Coulomb Balance used in conjunction with the PASCO Scientific Model SF-9586 Kilovolt Power Supply.

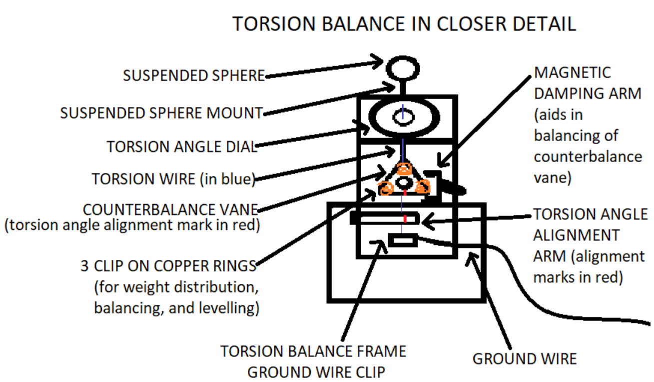

FIG. 3: A closer view of the Torsion Balance component of the PASCO Scientific Model ES-9070 Coulomb Balance.

of leakage currents from the power supply terminals' high voltage [4]. Working quickly so as to combat the time-sensitive effect of charge leakage, the sliding scale sphere was then adjusted to the appropriate position along the scale corresponding to the desired value of R. The torsion angle dial was then adjusted until the counterweight vane's alignment mark and the torsion balance alignment arm's alignment mark were lined up with each other. The values for R and θ were then recorded. This process was repeated for various values of R, and for each R value, three independent torsion angle readings were taken so as to be able to calculate uncertainty in θ. R could be read from the sliding scale to a precision of +/- 0.1 cm, and θ could be read from the torsion angle dial to a precision of +/- 0.5 degrees, however uncertainty in θ for each value of R was found using the standard deviation computed from all three θ values recorded for each R value.

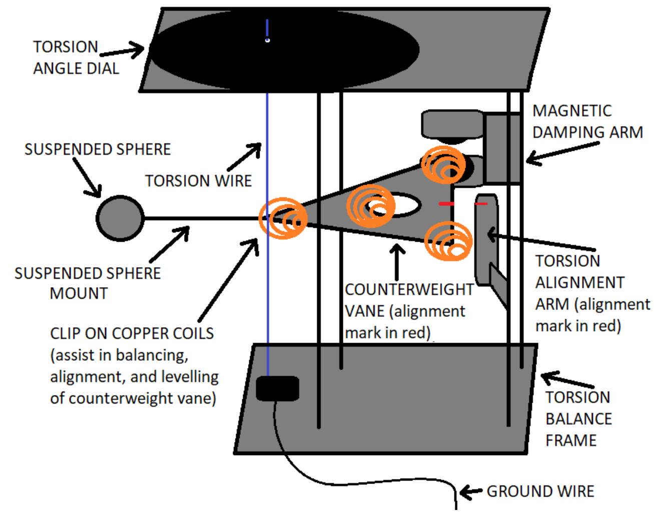

FIG. 4: A side view of the Torsion Balance component of the PASCO Scientific Model ES-9070 Coulomb Balance.

4. DATA ANALYSIS AND INTERPRETATION OF RESULTS

4.1. Fit Using Painted Spheres

A data fit using equation (9) was used to analyze the relationship between torsion angle θ in degrees and distance between sphere centers R in meters for the painted spheres. The 4 in the correction factor term provided in equation (2) was replaced with an additional fit parameter. This fit is depicted in Figure 5.

The points representing a greater distance R between spheres are seen to be visibly and consistently below the data fit indicated by the theory and model. This sparked curiosity, as the theory behind Coulomb's law when applied to spherical geometry suggests that the spheres would behave less predictably at closer distances, not farther ones [7] [4] [8], hence the use of the correction factor for small distances. In an effort to investigate this observed offset, the data fit using equation (9) described above was performed again, this time with the addition of an offset fit parameter. A plot of this fit is included in Figure 6.

Adding an offset fit parameter seems to rectify the observed disagreement between the data and the model, and yields an ϵ_0 value of 6.09×10^{-12} Farads per meter $\pm$ 6.11×10^{-13} Farads per meter. While this does not perfectly align with the accepted ϵ_0 vacuum permittivity

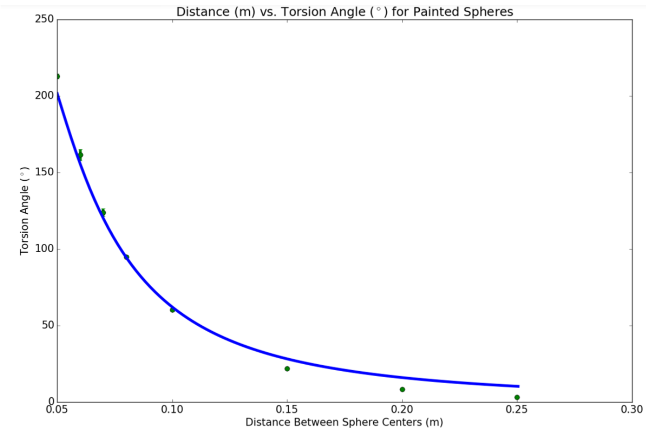

FIG. 5: Data fit of the distance between the sphere centers versus the corresponding angle of the torsion wire, fitted according to Coulomb's Law, with the aid of the manufacturer-suggested correction factor, for the spheres coated with carbon conductive paint.

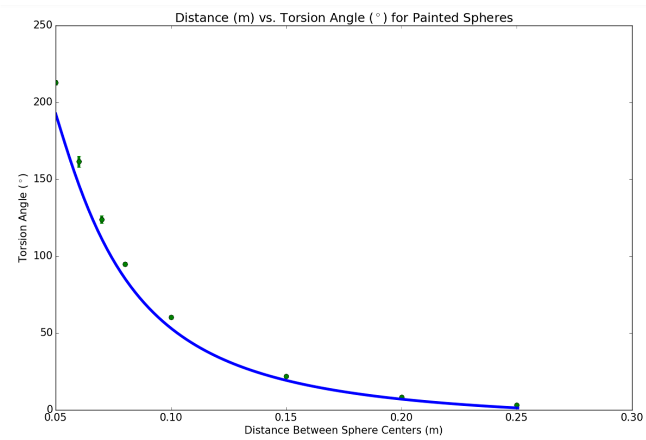

FIG. 6: Data fit of the distance between the sphere centers versus the corresponding angle of the torsion wire, fitted according to Coulomb's Law, with the aid of the manufacturer-suggested correction factor as well as an additive offset fit parameter, for the spheres coated with carbon conductive paint.

constant value of 8.85×10^{-12} Farads per meter [4], it is on the same order of magnitude, and agrees within four uncertainties. The data fit also yielded a value of 3.8788 in place of the 4 PASCO Scientific posits in their correction factor term detailed in equation (2) [4], as well as a value of -8.98 degrees for the additive offset parameter. A plot of the residuals for this fit is included in Figure 7.

This fit has a chi squared value of 0.2555, suggesting a reasonable fit between the data taken using the painted spheres and the model, with some overestimation of uncertainty. No trend is observed in the residuals, further suggesting reasonable agreement between the data and

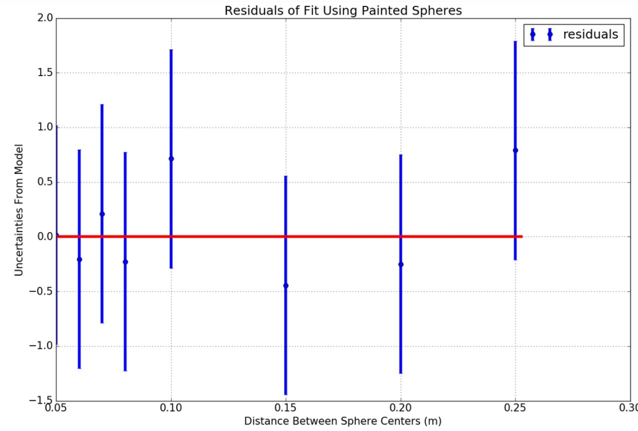

FIG. 7: Plot of residuals of the data fit with the aid of the manufacturer-suggested correction factor as well as an additive offset fit parameter, for the spheres coated with carbon conductive paint.

the model provided in equation (9) following the introduction of an additional additive fit parameter of -8.98 degrees.

Again using equation (9), data taken during the final lab period using the painted spheres, data taken during the final lab period using the original PASCO spheres, and data taken during Lab 3 using the original PASCO spheres were plotted alongside each other for comparison purposes. This plot aids in assessing whether or not the painted spheres are able to perform accurately in comparison with the original spheres designed for use with this apparatus. The additive fit parameter of -8.98 degrees is applied to the plot of the painted spheres data, but not the plots for either set of data taken using the original spheres. A figure of this plot is included below in 8.

The plots for both sets of data taken using the original spheres align overlap almost exactly, suggesting no significant systematic differences in the data collection process between those two sets. Furthermore the plot for the painted spheres follows a very similar curve, which in combination with the not-unreasonable value of ϵ_0 yielded by the painted spheres fit, suggests that the conductive spheres fabricated for use in this lab using MG Total Ground Carbon Conductive Paint are, in fact, a reasonably effective match for the original spheres provided by PASCO when it comes to torsion balance Coulombic force experiments. However, the plot for the data taken using the painted spheres is visibly and consistently lower by an additive offset of -8.98 degrees, sparking curiosity about the potential existence of a systemic factor present during the collection of that data set, yet absent in the other two.

After much discussion with Dr. Ackerman, brainstorming and data analysis in the laboratory setting, and eagle-eyed observation of the torsion balance apparatus

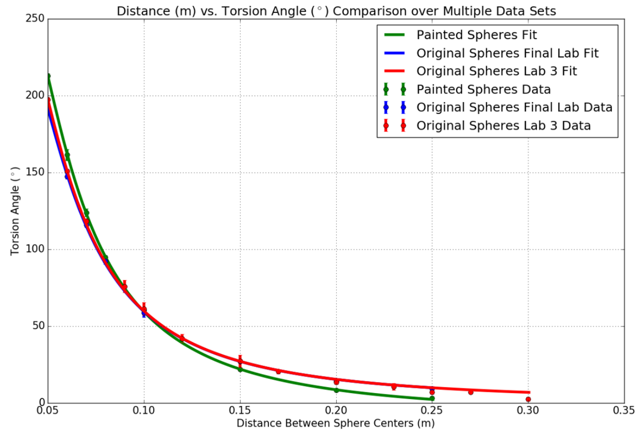

FIG. 8: Data fit of the distance between the sphere centers versus the corresponding angle of the torsion wire, fitted according to Coulomb's Law, with the aid of the manufacturer-suggested correction factor, for all three data sets.

as it sat undisturbed on the lab table equipped with the painted spheres, a potential rationale for this curious additive offset was reached. The effects of air currents in the lab due to the building's air conditioning vents were observed to be continually disturbing the angular alignment of the torsion balance in one direction from its grounded equilibrium position. PASCO Scientific discusses the vulnerability of this apparatus to air current disturbances in the lab manual, providing precedent for this potential explanation [4]. Furthermore, making certain directional assumptions about the air currents in question, it is plausible for the air currents to have affected the suspended sphere and counterbalance vane assembly more significantly in data points taken at larger sphere separation distances. Given the changes to the angular orientation of the suspended sphere assembly in response to increased or decreased sphere separation distance, the interaction that this changing angular orientation could have with an air current of a given incident angle as the suspended sphere assembly gradually becomes more or less perpendicular to the flow of air current, could potentially result in disagreement between data and model such as that observed in this experiment.

The near-exact overlap, high degree of alignment, and reasonable model agreement between both sets of data taken using the original spheres suggests that either these two data sets were both taken during off periods of the building's heating and cooling cycle when the air vents were not generating any current, or that perhaps something about the physical makeup of these spheres made them less susceptible to the effects of an air current. The latter option seems likely, as the original spheres are heavier than the painted spheres, requiring an additional three copper rings clipped on to the counterbalance vane in order to make the suspended sphere arm level, whereas the fabricated spheres were much lighter and did not require the addition of any metal rings. It stands to reason that the lighter, more delicate set of spheres would thusly be more susceptible to air currents in the lab environment, as the suspended sphere arm would be easier to push and swing with an air current if it were lighter.

5. CONCLUSIONS

Two sets of data collected using the original conductive spheres provided by the manufacturer, one taken during the final lab period, the other taken earlier this spring, were plotted against a third data set taken during the final lab period using a pair of newly manufactured conductive spheres built in lab using ping pong balls treated with carbon conductive paint. Each data set relates distance between the centers of the two charged isolated conductive spheres, and the angle recorded by a torsion balance in reaction to the Coulombic force between the two spheres. The three sets of data were fitted using a data fit which accounts for measurements of Faraday ice pail capacitance C (142.5 pF $\pm$ 0.3 pF), electrometer voltage V (42.0 V $\pm$ 2.0 V.), sphere radius a (0.0189 meters $\pm$ 2×10^{-5} meters for painted spheres and 0.019 meters for original spheres [4]), and torsion wire constant K (1.51474×10^{-6} Newtons per degree $\pm$ 4.76115×10^{-8} Newtons per degree), as well as a manufacturer-provided correction factor term meant to account for the deviation effect a sphere's geometry has on the math of the point charge model in the case of small distances between spheres. The data fit then yields a value for the vacuum permittivity constant ϵ_0, taking into account error propagation. An ϵ_0 value of 6.09×10^{-12} Farads per meter $\pm$ 6.11×10^{-13} Farads per meter was derived from the fit using the painted spheres, agreeing within 4 uncertainties with the accepted ϵ_0 value of 8.85×10^{-12} Farads per meter [4].

Coupled with the fit's chi squared value of 0.2555 and no observed trend in residuals, implying reasonable fit with the model but some overestimation in uncertainty, this ϵ_0 value suggests that fabricating conductive spheres by hand in lab using ping pong balls and carbon conductive paint is a productive and worthwhile educational exercise and a scientifically viable approach to Coulombic force experiments, should commercial spheres sold by lab equipment companies be unavailable or otherwise inaccessible. Excellent overlap and agreement was observed between both sets of original sphere data and the model, while the painted sphere data followed a similar pattern, but displayed a constant additive offset of -8.98 degrees. This offset was determined to likely be due to the effects of air currents from the building's air conditioning vents acting on the apparatus. Multiple unsuccessful attempts were made to isolate the apparatus from the air currents using plastic shields or relocate the apparatus to a room with no air conditioning vents. It is suspected that the painted spheres were more susceptible to the effects of air currents than their commercially purchased counterparts because they were much lighter, suggesting that perhaps conductive spheres made by hand in lab might be more stable and useful for practical experimental purposes if a slightly denser and less lightweight hollow plastic ball were to be used instead of a ping pong ball. Failing this, findings indicate that if an experiment were to be performed again using conductive spheres crafted from ping pong balls, it should be conducted in a room with low air flow and no strong air currents, or a more effective isolation chamber or shield of some sort must be built in which to house the apparatus in order to negate the effects of air current.

Considering the many applications of electrostatic interactions between spheres, namely in situations involving droplets of liquid, such as fuel injection and ink jet printing [1], the scientific properties observed in this experiment, or in any other involving the electrostatics of spherical objects, merit further consideration and study. The conductive paint used in this experiment proved for the most part to be an effective and accessible method of creating a conductive sphere for use in torsion balance experiments, adding to the scientific canon of means by which to build apparatuses capable of exploring Coulomb's original experiment, such as painting pith balls in gold leaf [10]. This method opens doors for further experimental design projects involving conductive paint which could better foster student understanding of conductivity, charge redistribution, and electrical engineering.

[1] J. Lekner, Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences **468** (2012).

[2] S. Syed Azim, A. Satheesh, K. Ramu, S. Ramu, and G. Venkatachari, Progress in Organic Coatings **55** (2006), URL http://www.sciencedirect.com/science/article/pii/S0300944005001918.

[3] T. Matsunaga, T. Nakayama, H. Wake, M. Takahashi, M. Okochi, and N. Nakamura, Biotechnology and Bioengineering **59** (1998).

[4] *Instruction Manual and Experiment Guide for the PASCO Scientific Model ES-9070 Coulomb Balance* (PASCO Scientific, 1989).

[5] D. J. Griffiths, *Introduction to Electrodynamics* (Prentice Hall, 1999).

[6] J. E. Mates, I. S. Bayer, M. Salerno, P. J. Carroll, Z. Jiang, L. Liu, and C. M. Megaridis, Carbon **87** (2015), ISSN 0008-6223, URL http://www.sciencedirect.com/science/article/pii/S0008622315000810.

[7] J. Slisko and R. A. Brito-Orta, American Journal of Physics **66** (1998).

[8] J. Lekner, Journal of Applied Physics **111** (2012).

[9] pascoscientific, *Coulomb's law experiment* (2015), URL https://www.youtube.com/watch?v=Pn64K0Epbzs.

[10] A. A. Martínez, Archive for history of exact sciences **60**, 517 (2006).