Coulomb Balance

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A PASCO Coulomb Balance was used to investigate the relationship between the force acting between two charges and the distance separating them. Before taking a correction factor into account, the data showed the relationship to be $F \propto R^{-1.4}$ with systematic error. After applying the correction factor, the relationship was found to be $F \propto R^{-2.01}$. This confirms Coulomb's Law: $F \propto R^{-2}$.

INTRODUCTION

In 1785, scientist Charles Augustus Coulomb discovered that the electrostatic force between two charged particles, assumed to be point charges, is proportional to the inverse of the square of the distance between them.[1] This is known as Coulomb's Law, commonly expressed as

$$F = \frac{1}{4\pi\varepsilon_o}\frac{q_1 q_2}{r^2} \qquad 1$$

where q_1 and q_2 are the charges of their respective particles, r is the distance between the two particles, and ε_o is the permittivity of empty space.[2]

To experimentally observe the above relationship, Coulomb created a torsion balance, which consisted of two identical conductive spheres encased in a glass container. One was kept stationary and the other free to revolve around a torsion wire. The measuring instrument was built into the glass jar.

EXPERIMENT

The PASCO model functions similar to the one used by Coulomb, except that only the position of the fixed sphere in the PASCO model can be changed. The amount to which the spheres attract or repel each other depends on the sign and magnitudes of the charges and the distance between them. However, if the charge is kept constant through the duration of all the trials, the distance between the charges becomes the principle factor.

When the sliding charge is set at a relatively far distance (around 30 cm) from the suspended charge, the force a cting between the charges is so small that it might not be noticeable to the human eye or it might not be able to overcome the force due to static friction acting on the pendulum assembly. As the sliding charge nears the suspended charge, the repulsion force between the two charges increases. In a torsion balance, the suspended charge is restricted to circular motion. As the suspended charge is repelled, it travels along the arc of the circle until it comes to equilibrium with the force acting on it from the sliding charge and the force acting on it as a result of the twisting of the torsion wire. After taking data and using the correction factor to make up for the size of the spheres, one should find that, first, the angle of deflection is proportional to the force acting between the charges and, second, the inverse square relationship between the force and distance holds true.

$$F \propto \frac{\theta}{r^2} \qquad 2$$

where θ is the torsion angle or the angle of displacement of the suspended charge due to the force acting between it and the stationary charge.

The spheres were grounded with a banana clip plugged into the ground of an outlet in the wall instead of the power supply. Then they were set apart at the maximum distance allowed by the slide assembly. Both spheres were equally charged using the charging probe connected to the positive output terminal of the power supply, which was set at approximately 6 kV. The sliding sphere was positioned at 20 cm on the ruler built into the slide assembly; this means that the centers of the spheres are 20 cm apart. The torsion knob on the top of the balance was slowly turned in the opposite direction that the pendulum assembly rotated until the suspended sphere returned to the zero position. The magnitude of the torsion angle was read from the torsion knob and the above process was repeated five times each for separation distances of 20, 14, 10, 9, 8, 7, 6, 5, and 4 cm.

One assumption of Coulomb's Law is that the charges are point charges. In the PASCO Coulomb Balance, the charged spheres are by no means point charges. They, in fact, have charges unevenly distributed about their surface, which can move about when a strong enough force acts on them. As the charged spheres approach each other, the charges move to opposite sides of their spheres. This causes the distance between the centers of the spheres to differ from the distance between the charge centers.

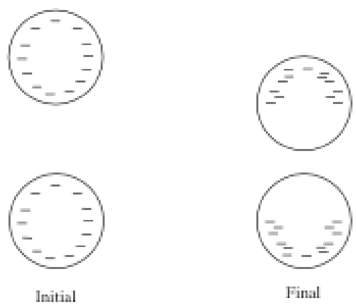

Fig. 1 – In this diagram, the initial state represents the two spheres when they are far apart and act, to some degree, as point charges. The final state shows the two spheres close enough where the surface charges repel each other and repel to opposite ends of the spheres.

This skewing of the distance values results in a lesser force, which implies that Coulomb's Law does not hold true for small separation distances, R, which is the distance between the centers of the spheres. This problem presents itself every time a Coulomb balance is used because it is impossible to create a balance using point charges, therefore, there will always be spheres with surface areas for charges to move.

To solve this problem, the original torsion angle, θ, was multiplied by the reciprocal of a correction factor[3], B, which takes into account the radius of the spheres[3], a = 1.9 cm, in relation to the separation distance, R, of the spheres.

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

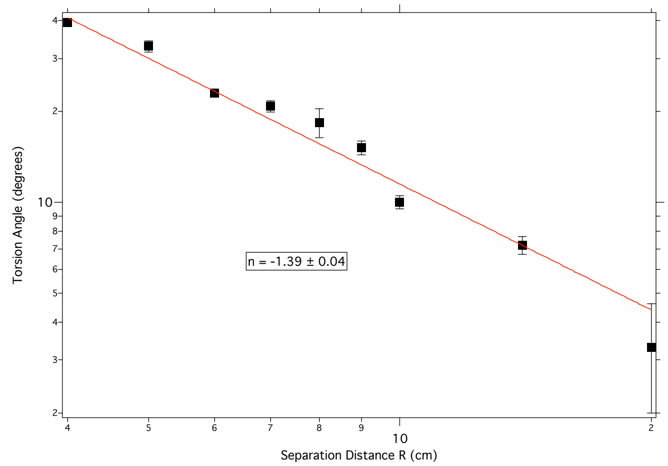

Fig. 2 – This is the log θ vs log R plot before the use of the correction factor on θ. The line is weighted heavier to the data points with less error.

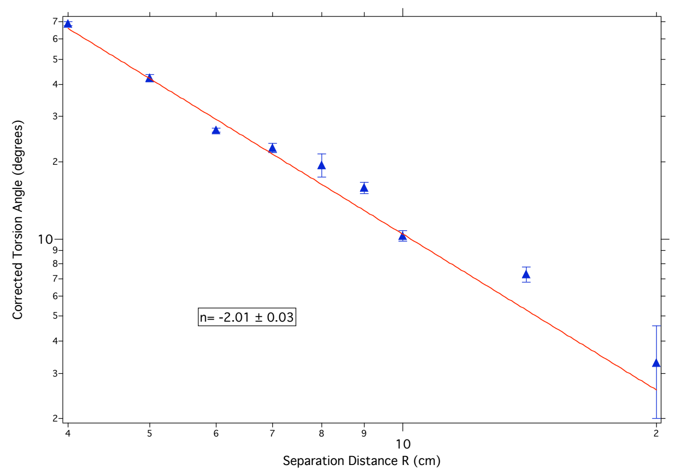

Fig. 3 – This is the log $\theta_{corrected}$ vs log R plot after the correction factor was applied to θ. This line is also weighted heavier towards data points with less error.

ANALYSIS AND INTERPRETATION

In Fig 2, the slope of the log θ vs log R plot, n, was –1.39 ± 0.04 or the relationship between the torsion angle and the distance was

$$\theta \propto \frac{1}{R^{1.39}} \qquad 4$$

The error of the slope in Fig 2 with respect to the theoretical value of n = -2.0, is 31% ± 2%.

Using equation 3, the slope of the log $\theta_{corrected}$ vs log R in Fig 3 was –2.01 ± 0.03, which means

$$\theta_{corrected} \propto \frac{1}{R^{2.01\pm 0.03}} \quad 5$$

The error of the slope in Fig 3 with respect to the theoretical slope is 0.5% ± 0.2%. Since the force acting between the spheres is proportional to the torsion angle, it can be stated that

$$F \propto \frac{1}{R^{2.01\pm 0.03}} \quad 6$$

Therefore, the data taken in this experiment agrees with Coulomb's Law in saying that the force is proportional to the inverse of the distance squared.

CONCLUSION

This experiment showed that, when set up correctly, the Coulomb balance is a useful and accurate tool for investigating interactions between charged particles. In this particular experiment, the balance was used to determine the relationship between the force and the distance. The relationship obtained through experimentation is shown in equation 6, which confirms the theoretical relationship presented in Coulomb's Law (see equation 1).

Other experiments investigating interactions between two charges can be done using the Coulomb balance. One can show the relationship between the force and the charge by holding the distance constant and varying the charges. Also, one can find the proportionality constant, $1/4\pi\varepsilon_o$, by applying a known force to the suspended sphere to get a corresponding torsion angle. This angle divided by the force will give the torsion constant for the wire. With the torsion constant and the gathered data one can determine the proportionality constant, as long as the charge is known.

ACKNOWLEDGMENTS

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1.) Halliday, Resnick, Walker, (1993) Fundamentals of Physics 4th ed. John Wiley & Sons, Inc. New York, pg. 639-640.
2.) Encyclopedia of Science & Technology 7th ed. (1992) McGraw-Hill, Inc. New York, vol. 4, pg. 485.
3.) Instruction Manual and Experiment Guide for the PASCO scientific Model ES-9070, Coulomb Balance, (1989) PASCO scientific.