

## The Cavendish Experiment 2 weights

**ATTENTION!!!** Entering the lab and approaching the setup, don't touch anything until you study the handout thoroughly. Re-alignment and rebuilding of the apparatus will take more than 24 hours!!!

### References:

Leybold, "Directions for use: Gravitation Torsion Balance" (available from the Resource Centre)  
Leybold Physics Leaflets: [http://downloads.gphysics.net/leybold/EXP/HB/E/P1/P1131\\_E.PDF](http://downloads.gphysics.net/leybold/EXP/HB/E/P1/P1131_E.PDF)

The references give some useful data about the apparatus; however, the description of the method should be taken from this handout.

You will also need a textbook "Physics for Scientists and Engineers", Volume 1, 8<sup>th</sup> Edition, by R. A. Serway and J. W. Jewett; for theory of torsional pendulum in Chapter 15, p. 451; and theory of universal gravitation in Chapter 13.

### Introduction

The Cavendish experiment was the first to allow a calculation of the gravitational constant ( $G$ ) by measuring the force of gravity between two masses in a laboratory framework.

The original experiment was proposed by John Michell (1724-1793), who first constructed a torsion balance apparatus. In 1793 the apparatus passed to Henry Cavendish who carried out a series of experiments published in 1798<sup>1</sup>. The original apparatus included a 1.8 m wooden rod with metal spheres attached to each end, suspended from a wire. Five 350 lb (195 kg) lead balls were placed nearby. The gravitational force exerted on the end weights was enough to cause the wire to twist.

From the twisting torque on the wire and the known masses of the spheres, Cavendish was able to calculate the value of the gravitational constant.

### Our experiment

In Fig. 1, the position labeled  $E$  is the equilibrium position of the balance with the heavy masses  $M$  not on their frame. When the large masses  $M$  are in position 1, the gravitational force  $F_g$  between each pair  $m$  and  $M$  is:

$$F_g = G \frac{Mm}{x_1^2} \quad (1)$$

where  $x_1$  is the distance between the centers of masses  $m$  and  $M$ .

Thus, the total torque  $\Gamma_g$  on the inner frame is:

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<sup>1</sup> Cavendish, H. "Experiments to determine the Density of the Earth", *Philosophical Transactions of the Royal Society of London*, (part II) **88** p.469-526 (1798)

$$\Gamma_g = G \frac{Mm}{x_1^2} 2d \cos \alpha_1 \quad (2)$$

where  $2d$  is the distance between the masses  $m$ . When the large masses  $M$  are in position 2, there is a similar equation with subscript 1 replaced by 2.

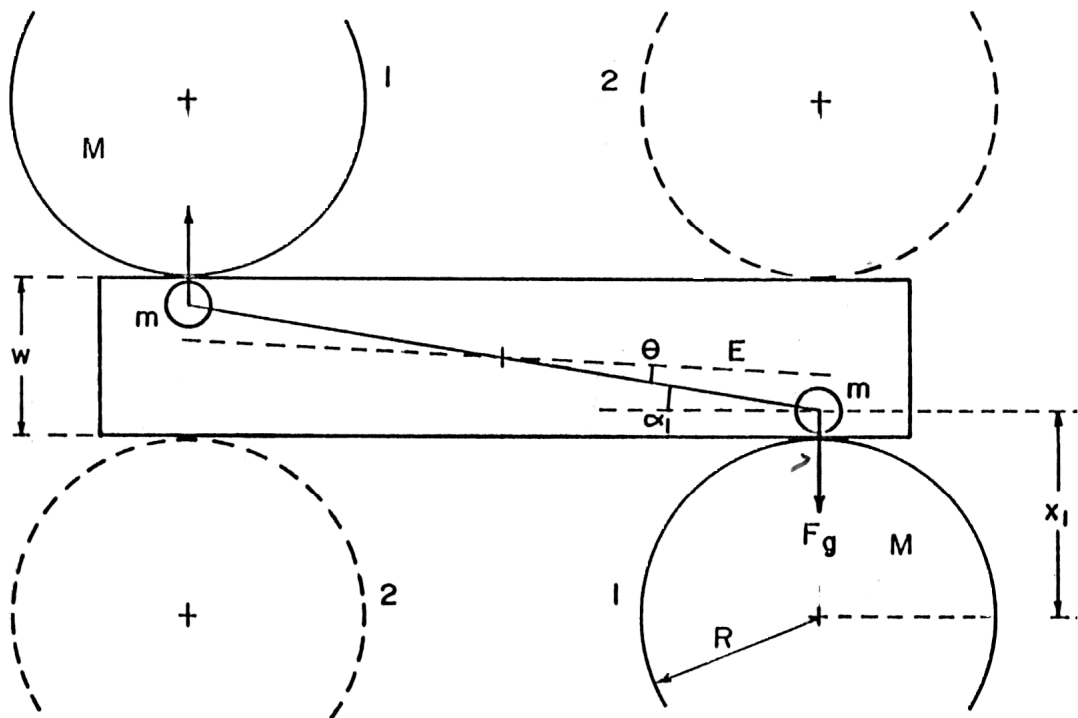


FIG.:1. Schematics of the Cavendish apparatus (top view)

At equilibrium, this torque is balanced by a torque from the wire supporting the inner frame. This torque is given by  $k\theta_1$  (where  $k$  is the torsion constant and  $\theta_1$  is the angle of twist of the wire).

$$G \frac{Mm}{x_1^2} 2d \cos \alpha_1 = k\theta_1 \quad (3)$$

The torsion constant can be determined by measuring the period  $T$  of oscillation as the frame approaches equilibrium.

$$T = 2\pi \left( \frac{I}{k} \right)^{1/2} \quad (4)$$

where  $I$  is the moment of inertia of the inner frame.

Assuming that the moment of inertia of the inner frame is just  $2md^2$ , equations 3 and 4 can be combined to eliminate  $m$ .

If the equilibrium position  $E$  is symmetric, then  $\theta_1 = \theta_2 = \alpha_1 = \alpha_2 \equiv \theta$ . Also, the distances between the masses  $m$  and  $M$  are equal:  $x_1 = x_2 = x$ , so it can be shown by simple geometry that:

$$x = R + \frac{w}{2} - d \sin \theta \quad (5)$$

where  $w$  is the width of the case and  $2d$  is the distance between masses  $m$  ( $2d = 10.00$  cm).

Including all the above approximations, the value of 'G' can be calculated.

Derive and show a formula to calculate G.

### Apparatus notes

Our apparatus consists of three main parts:

- The Cavendish balance itself. Details of the balance may be found in the manufacturer's (Leybold) notes;
- Low-power laser mounted on a special stand, detector and associated electronics;
- Acquisition software and computer.

A 2-element photodiode is mounted such as to replace the pen of the recorder. The output of the photodiode is connected to the *Cavendish Controller*, which outputs a voltage which is fed into the inputs of the recorder. Thus, the recorder will follow the laser beam reflected from the mirror of the Cavendish balance. The controller also contains a circuit which will cause the photodiode to seek for the beam.

The output signal is fed into a second controller, digitized and sent to the computer. The software used for collection of data and analysis is *LabVIEW* (National Instruments)

**CAUTION:** If viewed directly, the beam from even a low-power laser will cause permanent damage to your vision. Never look directly into the beam and also avoid looking at its reflection.

### Experimental notes

In this experiment, you will determine the equilibrium position of the reflected beam when:

1. The two large lead spheres are not mounted on the frame of the Cavendish balance.
2. The two large lead spheres are mounted and positioned fully clockwise on the balance.
3. The two large lead spheres are mounted and positioned fully counter-clockwise on the balance.
4. The two large lead spheres are not mounted on the frame of the Cavendish balance (if time permits, for verification of the equilibrium position after the experiment).

You will determine these equilibrium positions by analyzing the oscillations of the balance: it is not necessary to wait for the system to come to steady equilibrium. The recording will allow you to determine the period of oscillation of the balance, and therefore calculate the torsion constant of the wire support.

After setting up the system, it will take you not less than 45 minutes to acquire the data for each of three conditions for the large lead spheres. Thus, you should *carefully* read this section and begin taking data as soon as possible.

Insure that the balance is level, and that the inner frame holding the two small lead balls is swinging freely. The surface of sand under the balance must be smooth and flat.

Consider the apparatus is prepared before the session, and the balance is in equilibrium. The metal disc and thumb screw on the top of the balance adjusts the equilibrium position of wire supporting the inner frame. It should not need adjustment. If you suspect it does need adjustment **do not attempt to do so yourself but report the problem to the lab technologist at the Resource Center.**

Before you come to the labs, the system is thoroughly aligned by the lab technologist and does not need adjustments. You can just check the alignment by verifying whether the photodiode head tracks the beam.

In the aligned system, the incident and reflected beam lie in a plane that is perpendicular to the axis of rotation of the balance. Further, the reflected spot must strike the photodiode directly in the centre. If you find the alignment was damaged, invite the lab technologist to your setup and explain the problem. The alignment usually takes several hours; therefore, try to not disturb the prepared optical system. One way to align the system is to leave the recorder off; then you may slide the recorder on the support bench until the photodiodes are horizontally aligned with the beam. Now you may gently adjust the laser diode until the reflected beam strikes the photodiodes. In the course of making this adjustment, the balance will probably be disturbed and will start vibrating: wait a few minutes for it to settle down before proceeding. Check the alignment by turning on the recorder and the controller to see if the photodiode head tracks the beam.

The control on the lower-right of the recorder panel is labeled (roughly)  $\langle 0 \rangle$  and controls the zero-offset of photodiode arm. Do not adjust it once you started taking data. Similarly, do not adjust the laser between sets of data.

When the inner frame is oscillating back and forth you want to position the recorder so that the entire path of the oscillations is being tracked.

### **Data acquisition**

To open the data acquisition program, click on the 'Cavendish' shortcut, located on the desktop. However, the interface can be already prepared in advance, and you will not need to open the shortcut. Study the monitor interface and find the upper line with a number of functions that can be displayed and the row of command buttons just below. Be sure you have an active function "CH 1 vs TIME" at the utmost left upper position. Don't exercise with other buttons in the upper line.

Press the button "Click to Capture Data" at the row of commands. This allows you to begin/end a recording. The usual acquisition and recording time is about 45 minutes. The rescale is done automatically.

There is a 1:1 correspondence between the vertical units of amplitude on the display and the units on the recorder. To record two sets of data on same screen, don't press the button "CLICK HERE TO CLEAR DATA" between two data acquisitions.

Press the button "CLICK HERE TO PRINT CHART" to print the chart. To save data, press the button "CLICK HERE TO SAVE DATA". Data file is saved by default on C:\My Documents in .txt

format. If a new recording is started, the data file will be overwritten. To avoid this, rename the acquired data before beginning the next run. **Make sure you upload each data file in your memory stick before you start a new recording!**

**Note:** LabVIEW is a powerful graphical development environment, used for signal acquisition, measurement analysis, and data presentation. If you want to find out more about it, go to <http://www.ni.com/labview/>

**Questions** (answer the questions in your notebook; your answers will be marked)

- 1) Is the equilibrium position E really symmetric?
- 2) The torsion pendulum is clearly a damped harmonic oscillator. Is the motion *simple harmonic*? What effect does the damping have on the determination of the period?
- 3) Each mass  $m$  will also be attracted by the remote second mass  $M$ . What effect does this have on your result?
- 4) What is the dominant error in the determination of  $G$ ? Does the approximation being made have an effect comparable to this dominant error? If yes, what can be done about it?

*This experiment was revised in 2007 by Ruxandra M. Serbanescu. Previous versions: DH – 1987-88. Thanks to Phil Scolieri for interfacing the Cavendish Controller with LabVIEW.*

Last revised October 2011 by Natalia Krasnopolskaia