Instruction Manual

for

EB-03 Beck Ball Pendulum

Introduction

The Daedalon EB-03 Beck Ball Pendulum is a laboratory instrument for use in college and high school physics courses. It consists of a spring-operated gun and a pendulum. The gun shoots a steel ball that is caught by a catching mechanism in the bob of the pendulum. When the ball is caught, the pendulum swings upward and is held at its maximum height by a pawl and latching rack. Operated in this way, the EB-03 Pendulum is often called a "ballistic pendulum," and the maximum height of the pendulum can be used to determine the initial speed of the ball. With the pendulum removed (or positioned away from the gun), the gun can be used alone to launch the ball for the study of projectile motion.

The ballistic pendulum appears as an example in many well-known algebra-based [1] and calculus-based [2] textbooks, where it takes a somewhat different form. Strings or wires suspend a block of wood and a bullet is fired into the block, which moves upward. If the masses of the bullet and block are known, the bullet's initial speed can be calculated from the maximum height reached by the block. This type of ballistic pendulum is sometimes used in physics classes,[3] but it has two disadvantages when compared to the Beck Ball Pendulum. First, it requires the use of a firearm. Second, the very high speed of the bullet cannot easily be measured by another mechanical means for comparison with the speed obtained from the ballistic pendulum.

This manual describes the assembly, operation, and maintenance of the Daedalon EB-03 Beck Ball Pendulum. It also contains recommended experiments, sample data from those experiments, suggestions for other experiments, suggested questions for students, and a list of references. The references provide many sources of information about ballistic pendulums in general and the Beck Pendulum in particular; they also provide detailed information about the sources mentioned in the footnotes.

IMPORTANT

Before attempting the experiments, teachers should be sure they understand the operation and maintenance of the EB-03 Pendulum as described in this manual.

---

1 GIA, Example 7-9, p. 179; CUT, Example 8, pp. 199-200.
2 WOL, Example 11-2, p. 267; HAL, Sample Problem 10-2, pp. 200-201.

3 FRE, Experiment Mi-3, p. M-26.

DAEDALON CORPORATION
FAX (978) 745-3065, www.daedalon.com, e-mail: sales@daedalon.com

The parts of the EB-03 Pendulum are shown in Figure 1, the exploded view of the instrument. In this manual, numbers in square brackets refer to numbers on that figure. For example, the text might say ".. the ball storage post [41]..." because the ball storage post is item number 41 in the exploded view.

EB-03 Beck Ball Pendulum

RACK ASSEMBLY
1. RACK
2. SOCKET HEAD CAP SCREW (2)
3. RACK MOUNT
4. HEXHEAD CAP SCREW (2)
5. WASHER (2)

BASE ASSEMBLY
6. BASE
7. SLOTTED HEAD SCREW (4)
8. RUBBER FOOT (4)

PENDULUM ASSEMBLY
9. PENDULUM TRUSS
10. PENDULUM BOB
11. RUBBER BAND
12. BALL TRAP PLATE (3)
13. PIN (5)
14. PAWL

PENDULUM SUPPORT ASSEMBLY
15. KNURLED NUT
16. PENDULUM MOUNTING SCREW
17. SOCKET HEAD CAP SCREW
18. BEARING (2)
19. SHAFT
20. SHAFT HOUSING
21. MAST
22. HEXHEAD CAP SCREW (3)
23. WASHER (3)

GUN ASSEMBLY
24. HEXHEAD CAP SCREW (3)
25. WASHER (3)
26. TRIGGER RETURN SPRING
27. SOCKET HEAD SETSCREW
28. SOCKET HEAD CAP SCREW (4)
29. FACE PLATE
30. TRIGGER
31. STEEL WASHER
32. TEFLON WASHER
33. RAM
34. SPRING
35. GUIDE ROD
36. WASHER
37. SOCKET HEAD CAP SCREW
38. TRIGGER STOP
39. GUN HOUSING

BALL STORAGE
40. STAINLESS STEEL BALL
41. BALL STORAGE UNIT
42. NUT
43. WASHER
44. LOADING PLATE

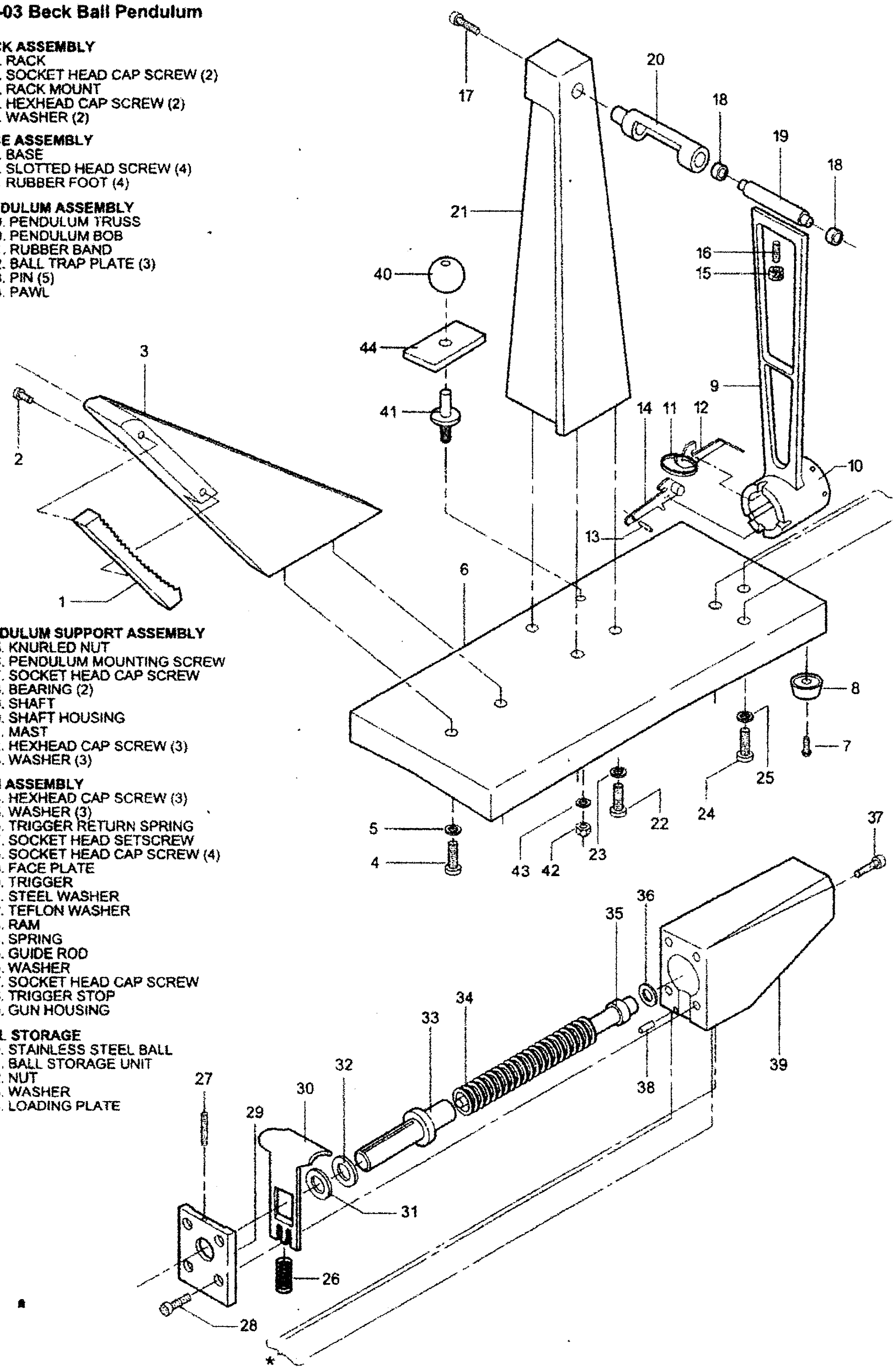

Figure 1

Part I – General Information

Unpacking and Assembly

Unpack the instrument slowly. Do not discard any packing materials until you are certain that no parts are missing and that the instrument has not been damaged.

To assemble the instrument, attach the pendulum truss [9] to the shaft [19] using the pendulum mounting screw [16] and the knurled nut [15]. Be sure that the step at the top of the truss matches the step in the shaft. The stainless steel ball [40] should be stored on the ball storage post [41].

Included with the instrument is a "loading plate" [44], a rectangular piece of aluminum about 5 cm by 3 cm with a hole in its center. The loading plate can be stored on the ball storage post under the ball.

Description of the Instrument

The body of the instrument consists of four aluminum castings: the mast [21], the rack mount [3], the gun housing [39], and the base [6].

The pendulum consists of the truss [9] and the bob [10], which are welded together. The pawl [14] and the ball trap plates [12] are held in the bob by hinge pins [13]. Common rubber bands [11] provide the restoring force for the trap plates. The pawl and the rack [1] together stop the pendulum at its maximum height. A step machined into the top of the pendulum truss [9] mates with a similar step in the shaft [19]. These steps allow the pendulum to be mounted correctly with the hinge pins facing the gun so that the catcher will work properly. The shaft is supported by ball bearings [18].

The ram [33] has three notches that can engage the trigger [30]. The gun is loaded by moving the ram until the trigger engages the first notch. As the ram moves toward the gun housing [39], it compresses the spring [34]; but the guide rod [35] does not move. To further depress the spring, the ram can be moved beyond the first notch to the second or third notch while the trigger is depressed. Before the gun is fired, the ball [40] is slid onto the guide rod. Pressing down on the trigger releases the ram, which rapidly pushes the ball away from the gun housing, firing the gun.

Operation of the Instrument

NOTE

Safety glasses should be worn whenever the spring gun is loaded or fired.

Preparing to Use the Gun without the Pendulum

Be sure that the pendulum is removed or is out of the way. When the gun is fired and the pendulum is not used, the ball will travel about 2.5 meters. Be sure that there are no obstructions in the anticipated path of the ball.

Place a barrier, such as a cardboard box, on the floor about 3.5 meters from the gun. (When the ball hits a tile floor, it might leave a small dent in the floor. If you wish to avoid these dents, place a piece of plywood flat on the floor where the ball is expected to hit.)

Practice firing the gun without the pendulum before firing it into the pendulum.

Preparing to Use the Gun with the Pendulum

Be sure that the pendulum is properly installed and free to swing.

Be sure that the knurled nut [15] is tight. Remember that the step machined into the top of the pendulum truss [9] must mate with a similar step in the shaft [19].

Be sure that two light rubber bands [11] are looped around the ball trap plates. (Rubber bands are supplied with the instrument. Use only rubber bands similar to the ones supplied.)

Be sure there are no obstacles between the end of the guide rod [35] and the pendulum bob [10]. (The ball will travel a very short distance before being caught by the trap plates.)

Before loading the gun, hold the pawl [14] in its "up" position and swing the pendulum up over the rack [1] to be sure there is proper alignment and clearance. Then let the pawl drop to the rack so that it holds the pendulum assembly up out of the way. (After the gun is loaded, swing the pendulum down to its free, vertical position.)

Loading the Gun

Put the loading plate [44] or the ball [40] on the end of the guide rod [35].

Push it toward the gun housing [39], moving the ram [33] and compressing the spring [34].

After about four centimeters of ram travel, the trigger [30] will move up into the first of three cross slots in the lower surface of the ram.

The gun is now loaded.

To cock the gun to its second position, load to the first position as just described. Then, while holding the loading plate or ball, depress the trigger and push the loading plate or ball another half centimeter so that the trigger clicks up into its second slot.

To cock the gun to its third position, repeat the above procedure and move the loading plate or ball another half centimeter so that the trigger clicks up into the third slot.

Loading the gun to the second or third position requires depressing the trigger while the gun is loaded and is not easy. Teachers might want to do this for students rather than having students do it themselves.

Always store the gun uncocked.

Firing the Gun

If the loading plate was used, be sure to remove it and replace it with the ball. This is very important.

Be sure that the pendulum is in the desired position and is properly secured.

Be sure that the anticipated path of the ball is clear.

Press down on the trigger with a firm even pressure. (As the gun "breaks in," the trigger will tend to work more smoothly.)

Maintenance of the Instrument

Inspect the instrument before each lab session or demonstration.

Periodically check the tightness of the four socket head cap screws [28] (1/4-20 x 1" Allen bolts) that hold the face plate [29] on the front of the gun. These must be tight. Because they are subjected to firing shocks of the gun, they tend to creep in their threads and loosen, especially when the gun is new.

The socket head cap screw [37] at the rear of the gun should be snug, but not tight.

Should the pawl [14] in the pendulum bob frequently fail to latch properly in the rack [1], the probable cause is a downward shifting of the rack lower end. Using the furnished hex wrench, loosen the two cap screws [2] that attach the rack. Hold the rack up in its proper position and tighten the screws. Check pawl clearance and adjust the rack position as needed.

Replace the light rubber bands [11] that activate the ball trap plates whenever they show any sign of deterioration. Use light bands similar to the ones supplied with the instrument. A heavier band will place too much stress on the hinge pins [13] at the front of the plates. (The hinge pins are 1/16"x3/4" stainless steel dowel pins.)

Store the instrument in a clean, dry place away from corrosive chemicals. Allow sufficient space so that the apparatus is not scratched or otherwise damaged by other hardware.

Part II - Experiments

NOTE

Safety glasses should be worn whenever the spring gun is loaded or fired.

Experiment 1 – Determining Ball Speed from Projectile Motion

Theory

In this experiment, the pendulum is not used. The spring gun is used to shoot the ball horizontally from a known height above the floor. The horizontal distance traveled by the ball before it hits the floor is used to determine the initial speed of the ball.

For balls shot from the spring gun, air resistance is negligible. The horizontal velocity, v, of the ball, therefore, remains constant until the ball hits the floor. If S_{xf} is the horizontal distance traveled by the ball before it hits the floor (see figure 2) and t_f is the time of the flight, then

$$V = S_{xf} / t_f \qquad (1.1)$$

S_{xf} can be measured easily, but t_f must be determined indirectly. While the projectile is moving horizontally, it also falls vertically in a simultaneous (but independent) motion under the influence of gravity. Since the vertical travel ends when the ball hits the floor, the time for the vertical travel is t_f, the same time as for the horizontal travel. If Y is the initial height of the ball and g is the acceleration due to gravity, then

$$T_f = (2Y / g)^{1/2} \qquad (1.2)$$

Combining equations (1.1) and (1.2) gives

$$V = S_{xf} / (2Y / g)^{1/2} \qquad (1.3)$$

S_{xf} and Y can easily be measured and the value of g is known, so equation (1.3) can be used to calculate the initial speed of the ball.

Procedure

1. Position the instrument near the edge of a table. The pendulum assembly should be removed or, as shown in Figure 2, held up by the rack.

(In Figure 2, the gun assembly, rather than the mast, is toward the edge of the table. Although not absolutely necessary, this makes measurement of ball height much easier.) With a bubble level, check to verify that the base is perfectly horizontal. If necessary, wedge the base with a few sheets of paper.

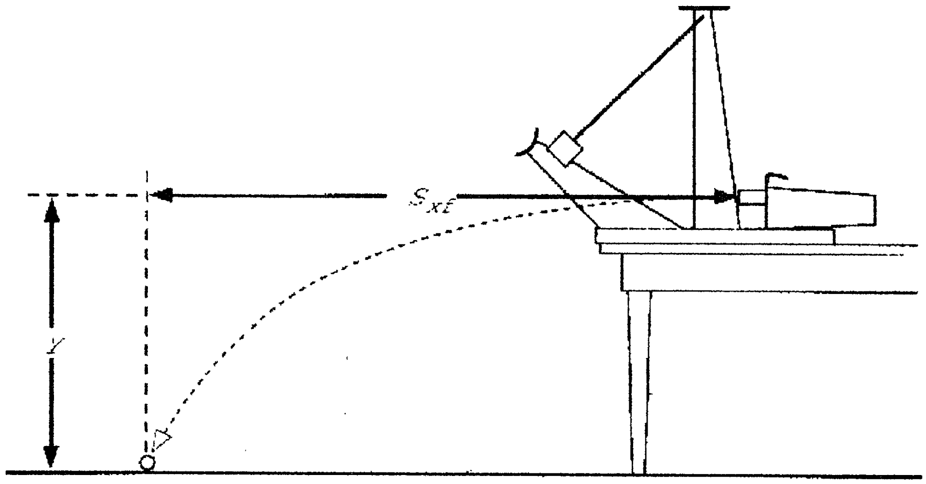

Figure 2

2. Use a plumb bob to mark on the floor the starting point of the ball's horizontal travel. Because the ball leaves the gun when the ram [33] is fully extended, place the ball on the guide rod [35] of the unloaded gun to do this measurement. If carbon paper is available, the mark can easily be created by taping a piece of paper to the floor, covering it with carbon paper, and using the plumb bob to mark the paper in the proper place.

3. When the gun is fired, the ball will travel about 2.5 meters. Be sure that there are no obstructions in the anticipated path of the ball. Place a barrier, such as a cardboard box, on the floor about 3.5 meters from the gun. When the ball hits a tile floor, it might leave a small dent in the floor. If you wish to avoid these dents, place a piece of plywood (or similar material) flat on the floor where the ball is expected to hit. If there is a rug on the floor, the plywood must be used.

4. Put the loading plate [44] or the ball [40] on the end of the guide rod [35]. Load the spring gun by pushing the ram [33] along the guide rod until the trigger [30] clicks into its first position. If the loading plate was used to load the gun, remove it and place the ball on the guide rod. Be sure that the ball is pushed all the way down the guide rod.

5. Be sure (again) that there are no obstructions in the anticipated path of the ball. Also, be sure (again) that the loading plate is not on

the guide rod. Then fire the gun and notice where the ball hits the floor.

6. Tape a piece of paper to the floor (or to the plywood) where the ball hit. Tape a piece of carbon paper over the paper. (If carbon paper is not available, do the experiment without it. The ball will dent the paper and the impact position can be determined.)

7. Fire the gun at least five times. Watch the travel of the ball each time. If the ball does not hit the paper every time, move the paper or add another sheet.

8. Using the marks on the paper, determine the average horizontal distance traveled by the ball. Use this for Sxf in equation (1.3).

9. Place the ball on the unloaded gun, and measure the distance from the bottom of the ball to the floor. (The measurement is from the bottom of the ball because the bottom of the ball hits the paper.) If plywood was not used on the floor, use this distance for Y in equation (1.3); otherwise, subtract the thickness of the plywood.

10. Use equation (1.3) to calculate the initial speed of the ball.

11. Be sure that the gun is left unloaded at the end of the experiment.

Experiment 2 Determining Ball Speed Using Conservation of Energy and Conservation of Linear Momentum

Theory

In this experiment, the ball is shot from the gun and is caught by the pendulum. The laws of conservation of energy and conservation of linear momentum are used to determine the ball's initial speed, which can be compared to the result from Experiment 1.

According to the law of conservation of linear momentum, the total linear momentum of the ball and pendulum must be the same before and after they collide (provided that no external forces act during the collision). Immediately before the collision, only the ball is moving; therefore, the momentum of the ball is the total momentum of the system. After the collision, the ball is trapped in the pendulum bob and the momentum of the system is the momentum of the ball and pendulum combination.

Thus:

$$\text{Momentum Before} = \text{Momentum After}$$

$$mv = MV \qquad (2.1)$$

where

m	is the mass of the ball
v	is the initial velocity of the ball
M	is the combined mass of the ball and the pendulum
V	is the velocity of the center of mass of the ball and pendulum combination

Although the masses can be measured in the laboratory, V is not known; therefore, v cannot be determined without more information. It is, however, possible to find the value of V in terms of other lab measurements based on the law of conservation of energy.

Several energy changes occur in the system from the time that the gun is fired until the pendulum (with the ball inside) swings to its maximum height. Initially, the ball travels toward the pendulum with considerable kinetic energy. In the short instant of the inelastic collision, much of the kinetic energy is transformed to heat; but some of it is retained by the pendulum/ball combination. Then, as the pendulum swings upward, its kinetic energy is transformed into gravitational potential energy. The latter energy is easy to find in the lab by measuring the height increase of the center of mass of the pendulum (with the ball inside).

K.E. immediately after collision = P.E. at maximum height

$$1/2\ MV^2 = Mgh \qquad (2.2)$$

where **g** is the acceleration due to gravity and h is the change in height of the center of mass. (See Figure 3)

Solving for V gives

$$V = (2gh)^{1/2} \qquad (2.3)$$

Substituting $(2gh)^{1/2}$ for V in equation (2.1) gives:

$$mv = M(2gh)^{1/2} \qquad (2.4)$$

$$v = (M/m)(2gh)^{1/2} \qquad (2.5)$$

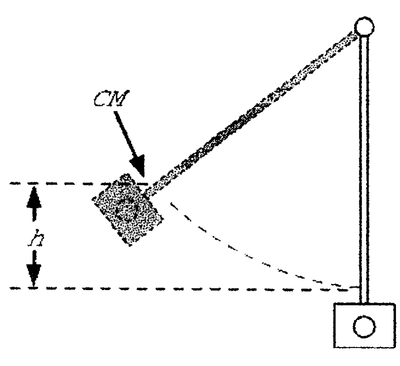

Figure 3

Important Note

Linear momentum is conserved only if no external forces act on the pendulum. As pointed out in two references, [4] an external force *does* act on the pendulum. Two other references [5] conclude that errors introduced by the external force may be balanced by friction between the pawl and the rack. In Experiment 3, angular momentum - which is truly conserved during the collision - is used instead of linear momentum.

Procedure

1. Remove the pendulum from the pendulum support.

2. With the ball in the pendulum bob [10], determine the center of mass of the pendulum using a knife-edge (e.g., a stiff metal ruler) to balance the pendulum as shown in Figure 4. Be sure that the knife-edge is perpendicular to the length of the pendulum. Use a washable marker to mark the outer narrow edges of the pendulum truss [9] where they touch the knife-edge. To simplify the measurement of h, be sure that there is a mark on the side of the truss that will be farthest from the mast [21].

NOTE: When determining the center of mass, be sure that the ball is in the pendulum bob.

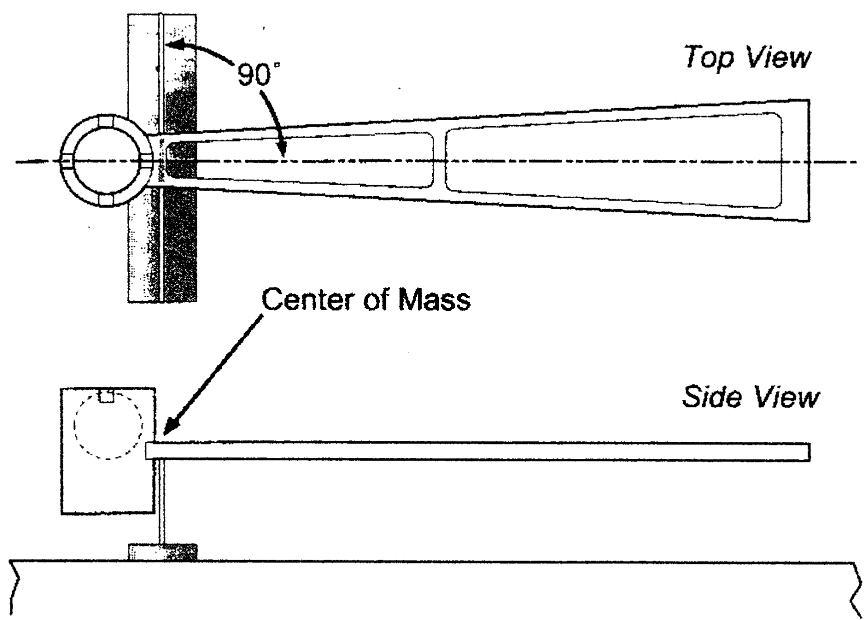

Figure 4

4 SAN, WIC
5 WAL1; WAL2, eq. (5.10a), p. 71.

3. Weigh the pendulum and ball together and record the total mass, M.
4. Weigh the ball separately and record its mass, m.
5. Place the pendulum on the pendulum support and wait for it to hang motionless in a vertical position. Be sure that the knurled nut [15] is tight.
6. Load the gun until the trigger [30] clicks into the same position used in Experiment 1.
7. Shoot the ball into the catcher and record the notch number of the rack notch where the pendulum stopped. (The numbers engraved in the rack are reference numbers; they do not directly give the notch number.) Do this several times.
8. Determine the average difference in height, h, of the center of mass when the pendulum is vertical and when the pendulum is held by the notches. (See Figure 3.)
9. Use equation (2.5) to calculate the initial speed of the ball.
10. Compare the result with the speed found in Experiment 1.
11. Be sure that the gun is left unloaded at the end of the experiment

Experiment 3 – Determining Ball Speed Using Conservation of Energy and Conservation of Angular Momentum

Theory

In this experiment, as in Experiment 2, the ball is shot from the gun and is caught by the pendulum. But in this experiment, the laws of conservation of energy and conservation of *angular* momentum are used to determine the ball's initial speed, which can then be compared to the results of Experiment 1 and Experiment 2. The use of angular, rather than linear, momentum is suggested in several references. [6]

According to the law of conservation of angular momentum, the total angular momentum of the ball and pendulum must be the same before and after they collide (provided that no external torques act during the collision). (The ball bearings [18] assure that essentially no external

---

6 GUP, SAC, SAN, WIC

torques act on the pendulum.) Immediately before the collision, only the ball is moving; therefore, the angular momentum of the ball is the total angular momentum of the system. After the collision, the ball is trapped in the pendulum bob and the angular momentum of the system is the angular momentum of the ball and pendulum combination. Thus, for angular moment about the pivot axis:

Angular Momentum Before = Angular Momentum After

$$mLv = \mathbf{I}\,\omega \qquad (3.1)$$

where

m	is the mass of the ball
v	is the initial velocity of the ball
L	is the perpendicular distance from the ball to the top of the pendulum truss. (See figure 5)
I	is the moment of inertia of the combined ball and pendulum when it swings about the pivot axis
ω	is the angular velocity of the combined ball and pendulum immediately after the collision

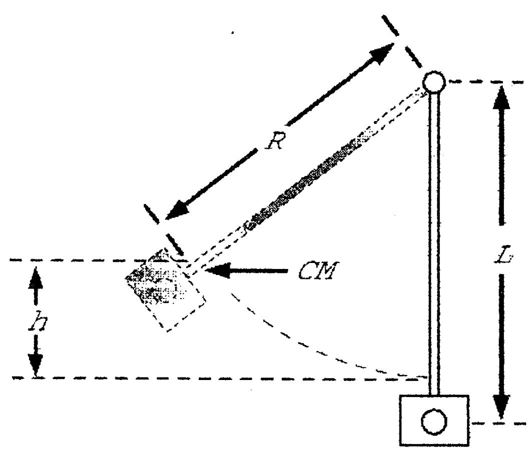

Figure 5

The moment of inertia, **I**, of the ball and pendulum combination cannot be measured directly. It can, however, be determined from T, the period of oscillation of the pendulum (with ball inside). T is related to the moment of inertia by: [7]

$$T = 2\pi\,(\mathbf{I}\,/MgR\,)^{1/2} \qquad (3.2)$$

7 FOW, Equation (8.4.5), p. 316.

where M is the mass of the ball/pendulum combination and R is the distance from the top of the pendulum to its center of mass as shown in Figure 5. Solving for **I** in equation (3.2) gives:

$$\mathbf{I} = T^2MgR \;/\; 4\pi^2 \qquad (3.3)$$

Since T, R and M can easily be measured, equation (3.3) gives a value for I to use in equation (3.1); but in order to determine v, ω must also be known. As in Experiment 2, energy conservation after the collision can be used to determine ω. This time, however, *rotational* (rather than *translational*) kinetic energy is used:

Rotational K.E. just after collision = P.E. at maximum height

$$1/2\ \mathbf{I}\omega^2 = Mgh \qquad (3.4)$$

which gives

$$\omega = (2Mgh \;/\; \mathbf{I})^{1/2} \qquad (3.5)$$

where h is the change in height of the center of mass and g is the acceleration due to gravity. Substituting **I** and ω from, respectively, equations (3.3) and (3.5) into equation (3.1) and solving for v gives

$$v = MgT\,(R\,h/2)^{1/2} \;/\; mL\pi \qquad (3.6)$$

Procedure

1. Follow steps 1 through 8 of Experiment 2. Then proceed with the steps below.
2. Measure the distance L shown in Figure 5. This is the distance from the center of the ball to the top of the pendulum truss when the ball is in the pendulum.
3. Measure the distance R shown in Figure 5. This is the distance from the pendulum suspension to the center of mass of the ball/pendulum combination.
4. Find the period, T, of the pendulum (with the ball inside) by timing at least ten swings and then dividing by the number of swings. Equation (3.2) assumes that the amplitude of the oscillation is small; so do not displace the pendulum by more than about five degrees when starting the swing.

NOTE: When determining the period, be sure that the ball is in the pendulum bob.

5. Use equation (3.6) to calculate the initial speed of the ball.
6. Compare the result with the results found in Experiments 1 and 2.

7. Be sure that the gun is left unloaded at the end of the experiment.

Experiment 4 - Hitting a Target

NOTE

Because the ball might ricochet from the ring or ring stand, it is especially important that safety glasses be worn during this experiment.

Theory

In this experiment, the pendulum is not used. The gun is used to shoot the ball horizontally from a known height above the floor. The ball should go through a ring located at a calculated position.

NOTE: To do this experiment, the initial velocity, v, of the ball must have been determined in one of the other experiments.

As explained in Experiment 1, the horizontal velocity of the ball remains constant until the ball hits the floor. (See equation (1.1).) Therefore S_x, the horizontal distance traveled by the ball in time t, is:

$$S_x = v\,t \qquad \text{for} \quad 0 \le t \le t_f \qquad (4.1)$$

where t_f is the time of flight of the ball and v is its initial velocity.

The vertical motion of the ball is simply free fall from an initial height Y. So, S_y, the vertical position of the ball at time t is:

$$S_y = Y - 1/2\, gt^2 \qquad \text{for} \quad 0 \le t \le t_f \qquad (4.2)$$

If t_1 is a particular time during the flight and v is known from a previous experiment, then S_{x1} and S_{y1}, the values of S_x and S_y at t_1, can be calculated from equations (4.1) and (4.2). If a ring supported by a ring stand is placed at the calculated location ($x = S_{x1}, y = S_{y1}$) and the ball is shot from the gun, the ball should go through the ring. (See Figure 6.)

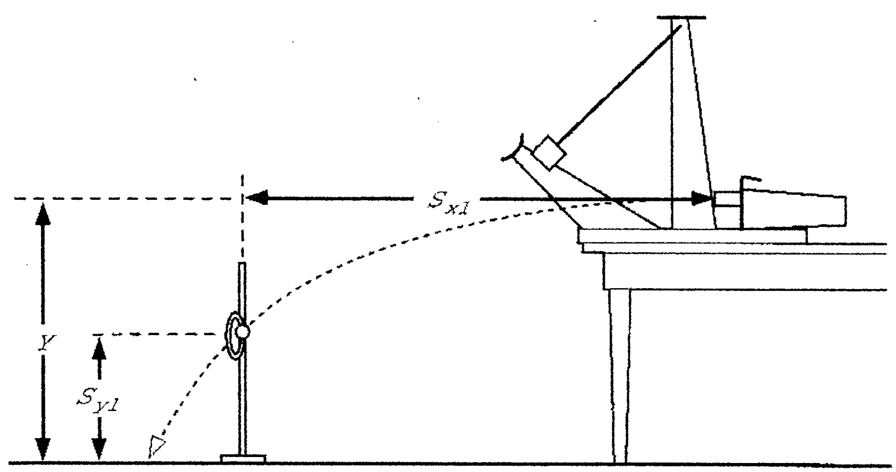

Figure 6

Procedure

1. Set up the instrument as described in Step 1 of Experiment 1.
2. If the horizontal range, S_{xf}, is not known from Experiment 1, shoot the ball once or twice to determine its approximate horizontal range.
3. Choose a distance that is between .4 and .6 times the horizontal range. Call this S_{x1}.
4. Use equation (4.1) and the value of v from a previous experiment to calculate t_1, the time at which $S_x = S_{x1}$.
5. Measure Y, the height of the gun, as described in Step 9 of Experiment 1.
6. Use equation (4.2) and the calculated value of t_1 to calculate S_{y1}.
7. Set up a ring stand to support a ring at the calculated position ($x = S_{x1}, y = S_{y1}$) as shown in Figure 6. Because the ball might bounce off the ring or the ring stand, be sure that the area around the ring stand is clear of people and objects.
8. Load the gun until the trigger clicks into the same position used in Experiment 1.
9. Shoot the ball from the gun. It should go through the ring!

Be sure that the gun is left unloaded at the end of the experiment.

Experiment 5 – Measuring the Speed of the Ball Electronically

NOTE

Because the ball might ricochet from the photogate assembly, it is especially important that safety glasses be worn during this experiment.

This measurement can be done at the same time as Experiment 1. Doing the two simultaneously has the advantage that the speed is determined in two different ways for the *same* flight of the ball.

Theory

In this experiment, the pendulum is not used. The spring gun is used to shoot the ball horizontally. Almost immediately after leaving the gun, the ball goes through a Daedalon EA-24 Photogate that controls a Daedalon ET-40 Electronic Stop Clock. The photogate consists of an infrared LED (light emitting diode) and an infrared photodiode. The LED is an infrared light source and the photodiode is an infrared detector.

When the ball passes between the source and the detector, the light beam is interrupted and the stop clock starts timing. When the light beam is no longer interrupted, the stop clock stops timing. The stop clock is an electronic stopwatch that starts when the ball cuts off the light beam and stops when the light beam reappears.

Procedure

1. Measure the "length" of the ball. This is the height of the cylinder that is the hole drilled in the ball, and it is slightly less than the diameter of the ball. This measurement is best done with a digital caliper or a vernier caliper. Call this "length" *d*.

2. Set up the instrument as described in Step 1 of Experiment 1.

3. When the gun is fired, the ball will travel about 2.5 meters. Be sure that there are no obstructions in the anticipated path of the ball. Place a barrier, such as a cardboard box, on the floor about 3.5 meters from the gun. When the ball hits a tile floor, it might leave a small dent in the floor. If you wish to avoid these dents, place a piece of plywood (or similar material) flat on the floor where the ball is expected to hit.

4. Position the EA-24 Photogate as shown in Figure 7. Note that the photogate is supported by a block that raises it to the proper height. The photogate should be free to move in case the ball hits it. Therefore, do **not** clamp the photogate to the pendulum base [1], the rack mount [3] or the table.

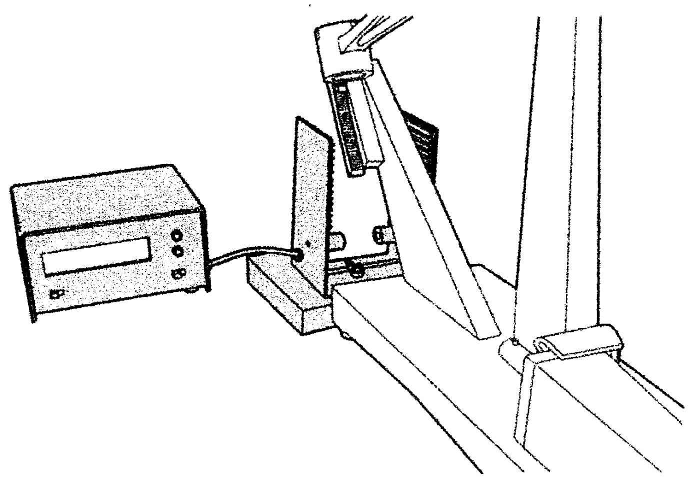

Figure 7

5. Connect the EA-24 Photogate to the "Start/ΔT" connector on the rear of the ET-40 Stop Clock. (The "Stop" connector is not used, and nothing should be connected to it.)

6. Place the ball on the guide rod [35], but do *not* load the gun.

7. Be sure that the photogate is aligned as shown in Figure 7. This is very important because the ball must be at the proper height and it must pass between the LED and the photodiode without touching either one.

If the ball is not aligned as shown in Figure 7, make the needed adjustments, which might include changing the thickness of the block supporting the photogate. Be sure that the gun is not loaded. (Do **not** look straight down the guide rod [35] at the ball when the gun is loaded.)

8. Connect the stop clock to a power source and turn it on. Be sure that the stop clock is in "Memory" mode and then push the "Reset" button.

9. Determine where the photogate will go if the ball hits it. Be sure that the photogate will not hit a person or a hard object. To prevent the photogate from going too far, consider taping the photogate cable to the table.

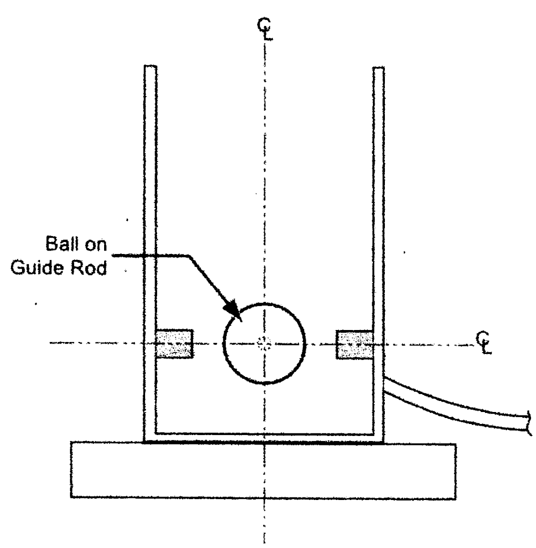

Figure 8

10. Load the gun. (If you use the loading plate [44] to load the gun, be sure to remove it and replace it with the ball after the gun is loaded.)

11. Again be sure that the photogate is aligned as shown in Figure 8, but do **not** look straight down the guide rod [35] at the ball when the gun is loaded.

12. Shoot the gun and record the time displayed on the stop clock. Call this time t.

13. Calculate the speed, v, of the ball ($v = d/t$). (This calculation assumes that an object of length d cut off the infrared beam. If the ball was too high or too low, a smaller object will effectively cut off the beam and the calculated speed will be too high. If repeated trials yield a high value for v, try raising or lowering the photogate slightly.)

14. Be sure that the gun is left unloaded at the end of the experiment.

Bright incandescent lights, such as those used when making a video recording, emit considerable infrared radiation. This radiation can prevent the photogate from detecting the ball. Keep this in mind if you plan to simultaneously analyze the motion with the stop clock and a video recorder.

Part III – Sample Data From Experiments

This sample data was gathered in the laboratory on one EB-03 Pendulum. Results for other instruments should be similar, but not necessarily identical.

All of the sample data was gathered with the gun loaded to its first position.

Sample Data From Experiment 1

EXPERIMENT 1

MEASURING BY PROJECTILE MOTION

Shot Number	S_{xf} (cm)
1	272.5
2	274.0
3	275.7
4	277.8
5	278.2
6	281.2
Average	**276.6**

Description	Symbol	Value	Units
Average range	S_{xf}	276.6	*cm*
Distance fallen	**Y**	99.8	*cm*
Acceleration due to gravity	**g**	980	*cm/s²*
Fall time [from eq. (1.2)]	t_f	0.451	*s*
Initial speed of ball [from eq. (1.3)]	**v**	613	*cm/s*

Sample Data From Experiment 2

EXPERIMENT 2

MEASURING BY CONSERVATION OF LINEAR MOMENTUM & ENERGY

Description	**Symbol**	**Value**	**Units**
Mass of pendulum with ball	**M**	263.1	***grams***
Mass of ball	**m**	61.0	***grams***
Average change in height of c.m.	**h**	11.5	***cm***
Acceleration due to gravity	**g**	980	***cm/s²***
Initial speed of ball [from eq. (2.5)]	**v**	648	***cm/s***

Sample Data From Experiment 3

EXPERIMENT 3

MEASURING BY CONSERVATION OF ANGULAR MOMENTUM & ENERGY

NOTE: M, m and h were determined during Experiment 2. Only L, R, and 10T were measured specifically for Experiment 3.

Description	**Symbol**	**Value**	**Units**
Mass of pendulum with ball	**M**	263.1	***grams***
Mass of ball	**m**	61.0	***grams***
Change in height of c.m.	**h**	11.5	***cm***
Distance from the ball to top of pendulum	**L**	30.7	***cm***
Distance from top of pendulum to c.m.	**R**	27.3	***cm***
Time for 10 periods of oscillation	**10T**	10.8	***s***
Period of oscillation	**T**	1.08	***s***
Acceleration due to gravity	**g**	980	***cm/s²***
Initial speed of ball [from eq. (3.6)]	**v**	593	***cm/s***

Sample Data From Experiment 4

EXPERIMENT 4
HITTING A TARGET

Description	Symbol	Value	Units
Average range [from Experiment 1]	S_{xf}	276.6	*cm*
Initial speed of ball [from Experiment 1]	**v**	613	*cm/s*
X-position of target [taken as .5S_{xf}]	S_{x1}	138.3	*cm*
Time at which $S_x = S_{x1}$ [from eq. (4.1)]	t_1	.226	*s*
Y-position of target [from eq. (4.2)]	S_{y1}	74.8	*cm*

Sample Data From Experiment 5

EXPERIMENT 5
MEASURING ELECTRONICALLY

Description	Symbol	Value	Units
"Length" of ball	**d**	2.43	*cm*
Time displayed on stop clock	**t**	.0035	*s*
Speed of ball [$v = d/t$]	**v**	694	*cm/s*

Part IV - Suggestions for Additional Experiments

Determine the initial speed of the ball by an alternative method.

For example, make a video recording of the flight of the ball and analyze the video field by field to determine the horizontal velocity of the ball.

As discussed in two of the references, [8] the rack and pawl add some friction to the system. Hold up the pawl with a rubber band (use one larger than those used on the trap plates), and use an alternate method (e.g. video recording) to determine the change in height of the pendulum c.m (center of mass). (Be sure to catch the pendulum before it crashes back into the gun.) Use this change in height to determine the initial speed of the ball.

In Experiment 1, the base of the gun was parallel to the floor. Investigate the trajectory of the ball when the gun is not parallel to the floor. Tilt the base of the instrument so that the guide rod [35] is not parallel to the floor. Try different angles. Consider these questions:

The horizontal range of a projectile is often defined as the horizontal distance a projectile travels before returning to its initial height. For what launch angle is the horizontal range maximum? (Since the initial and final heights need to be equal, this experiment is best done with the instrument on the floor and with a horizontal target at the height of the gun.)

If the launch height is not the same as the target height, for what launch angle is the target distance maximum? As discussed in several references,[9] this problem is more difficult than the previous one. (Since the initial and final heights will not be equal, this experiment can be done with the instrument on a table as in Experiment 1.)

NOTE: When the base is tilted, the ball will have an initial upward velocity. Therefore, it is especially important that safety glasses be worn during this experiment.

Even with the pawl held up by a rubber band, there is still some friction in the system and the pendulum loses some energy during its motion. Observe the oscillation of the pendulum and develop a model for its damped motion. From the model, determine what the change in height would have been without any damping. Use this change in height to determine the initial speed of the ball.

---

8 WAL1, WAL2

9 BRO, BAC1, BAC2; BRO and BAC1 discuss previous papers on this topic.

Part V - Questions for Students

1. In Experiment 3, at least ten swings of the pendulum are timed and the time is divided by the number of swings to get the period, T. If a stopwatch is used for the timing, why is this method much better than timing just one swing?

2. In Experiment 4, equation (4.1) is used to calculate t_1, which is then used in equation (4.2) to calculate S_{y1}. Combine equations (4.1) and (4.2) to give a new equation that can be used to calculate S_{y1} directly from S_{x1} without first calculating t_1.

3. In Experiment 1, develop equations for KE_i, the kinetic energy of the ball as it leaves the gun, and KE_f, the kinetic energy of the ball when it hits the floor. Explain the difference.

4. In Experiment 4, at what angle should the ring be tilted to maximize the probability that the ball will go through it? (HINT: First determine the x and y velocity components when the ball is going through the ring.)

5. Experiment 2 assumes conservation of linear momentum. But in the Beck Pendulum (and in other similar devices) linear momentum is not conserved if the system is taken to consist of the ball and the pendulum assembly. If linear momentum is not conserved, there must be an external force applied. What is the external force? Where is it applied?

6. Using v and ω from Experiment 3, calculate the *linear* moment immediately before and immediately after the collision. The results might surprise you. Try to explain them. (There is no sense doing this with v and V from Experiment 2. Why?)

7. Let KE_i and KE_f be, respectively, the kinetic energy immediately before and immediately after the collision in Experiment 2. Show from theory that

$$KE_f/KE_i = m/M$$

   where m is the mass of the ball and M is the mass of the ball and pendulum together.

8. In Experiment 3, the period (T) of the pendulum is measured with the ball in the

bob. Try measuring the period with the ball removed from the bob. The new period will not be very different. Why might this be?

9. The classic ballistic pendulum shown in Figure 9 appears as an example in many textbooks. Strings or wires suspend the block of wood and a bullet is fired into the block, which rises a distance h. The textbooks do not talk about angular momentum because in this device linear momentum really is conserved. Why?

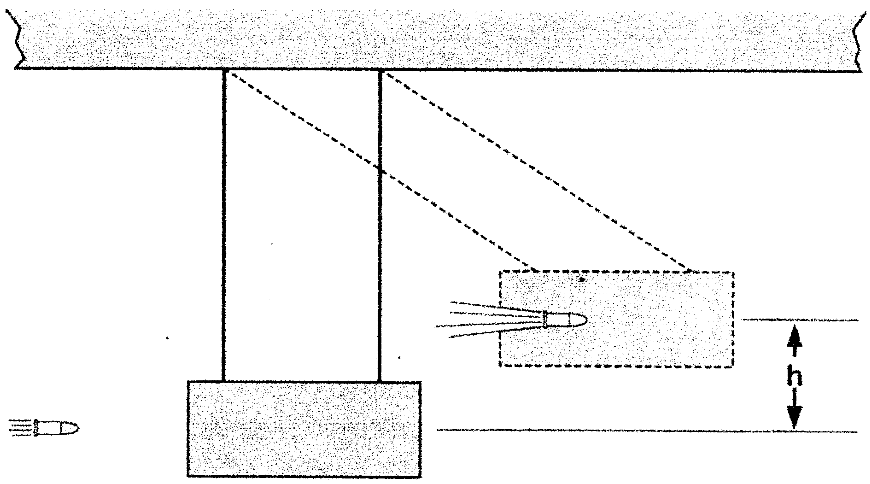

Figure 9

10. The steel ball shot from the spring gun is a sphere with a cylinder drilled through its center. Let R and r be, respectively, the radius of the sphere and the cylinder. Derive a formula for the height of the cylinder in terms of R and r. (This formula can be used to determine the "length" of the ball, which is needed in Experiment 5.)

George Caplan, Department of Physics, Wellesley College-December 2004 wrote this manual. His assistance is gratefully acknowledged.

References

BAC1 M. Bace, S Ilijic, and Z. Narancic, " Maximizing the range of a projectile," Eur. J. Phys. **23** (2002) 409–411.

BAC2 M. Bace, et al., "The envelope of projectile trajectories," Eur. J. Phys. **23** (2002) 637–642.

BRO R.A. Brown, "Maximizing the range of a projectile," Phys. Teacher **30** 344–347 (September 1992)

CUT J.D. Cutnell and Kenneth W. Johnson, *Physics*, 5th ed. (John Wiley and Sons, 2001).

FOW G. R. Fowles and G. L. Cassidy, *Analytical Mechanics*, 6th ed. (Brooks/Cole, 1999).

FRE G. D. Freier and F. J. Anderson, *A Demonstration Handbook for Physics*, 3rd ed. (American Association of Physics Teachers, 1996).

GIA D.C. Giancoli, *Physics*, 4th ed. (Prentice Hall, 1995).

GUP R.D. Gupta, "Blackwood pendulum experiment and the conservation of linear momentum," Am. J. Phys. **53** (3) 267-269 (March 1985).

HAL D. Halliday, R. Resnick and J. Walker, *Fundamentals of Physics*, 6th ed. (John Wiley and Sons, 2003).

SAC A. Sachs, "Blackwood pendulum experiment revisited," Am. J. Phys. **44** (2) 182-183 (February 1976).

SAN R.R. Sandin, "Nonconservation of linear momentum in ballistic pendulums," Am. J. Phys. **41** (12) 426-427 (March 1973).

WAL1 C.N. Wall, "Apparatus review: the beck ball pendulum," Am. J. Phys. **36** (12) 1161-1163 (December 1968).

WAL2 C.N. Wall, R.B. Levine, F.E. Chritensen, *Physics Laboratory Manual*, 3rd ed. (Prentice Hall, 1972).

WIC E. Wicher, "Ballistics pendulum," Am. J. Phys. **45** (7) 681-682 (July 1977).

WOL R. Wolfson and J.M. Pasachoff, *Physics for Scientists and Engineers*, 3rd ed. (Addison-Wesley, 1999).