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Collisions–Conservation of Momentum

revised June 15, 2009

(*Only students in PHYS 115 and PHYS 121 do this experiment; PHYS 123 students will perform the Collisions in Two Dimensions Experiment*.)

Learning Objectives:

During this lab, you will

1. communicate scientific results in writing.
2. estimate the uncertainty in a quantity that is calculated from quantities that are uncertain.
3. test a physical law experimentally.

A. Introduction

The law of conservation of momentum is one of the great conservation laws in physics. Unlike energy, which is a scalar quantity, momentum is a vector. Also unlike energy, momentum can have only one form, the mass of an object multiplied by its velocity, or $\vec{P} = m\vec{v}$. Energy, on the other hand can take many forms: kinetic, potential, thermal, etc. Thus, there is rarely any ambiguity about momentum conservation; for an isolated system, the vector sum of the momenta of the individual particles before an interaction must be equal to the vector sum of the momenta after the interaction. This principle applies even to those reactions in which new particles are created, initial particles were destroyed (*i.e., mass converted into energy)*, or mechanical energy was lost to friction or deformation.

You will consider collisions between two carts on a low-friction track. Under ideal circumstances, *i.e.*, when no external forces

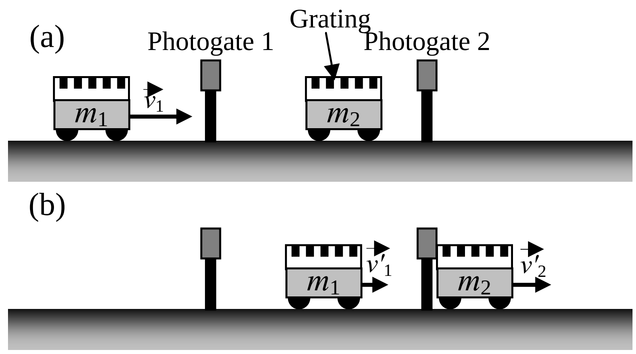

Figure 1: Schematic of experiment (a) before collision and (b) after collision.

are exerted on either cart, the net sum of the momenta of the two carts must be unchanged, so that the momentum gained by one cart is equal and opposite to the momentum lost by the other, $\Delta\vec{P}_2 = -\Delta\vec{P}_1$. In an *elastic* collision, the total mechanical energy is unchanged as well. An *inelastic* collision is one in which mechanical energy is either lost or created in the collision. You will investigate elastic collisions as well as both types of inelastic collisions in this experiment.

You must write a paper for this lab worth 60 points.

B. Apparatus

You will use a PASCO track with two low-friction carts, mass bars, a spirit level and a computer with *Logger Pro* software. To measure the motion of the carts, you will use a grating and two photogates. The grating is a set of parallel black lines on a transparent holder. A photogate is simply a light-emitting diode aimed at a light sensor. It detects motion by sensing the alternate transmission and blocking of light as a grating, mounted on a cart, slides by. Knowing the thickness of the lines on the grating and the time in each light cycle lets the computer calculate the speed of the cart. A schematic diagram of the experiment is at Figure 1.

C. Theory

C.1. Elastic Scattering

When two objects (*1 and 2*) collide and scatter elastically, both the total mechanical energy and the total momentum are conserved in the interaction. Consider a system of two particles constrained to move in one dimension. A projectile particle (*1*) has some initial velocity towards a target particle (*2*), which is at rest before the collision (*so the target's initial momentum and energy are zero*). Our conservation equations for momentum and energy can be written as

$$\vec{P}_1 = \vec{P}_1' + \vec{P}_2' \qquad (1)$$

and

$$K_1 = K_1' + K_2', \qquad (2)$$

where $\vec{P} = m\vec{v}$ are the momenta , $K = ½Mv^2$ are the kinetic energies, unprimed variables apply before the collision and primed variables apply after the collision. Note that Equation 1 is a vector equation, so even though the motion is in one dimension, the direction is important.

C.2. Totally Inelastic Scattering

As noted above, an inelastic collision involves some loss of mechanical energy. In certain types of collisions, the energy loss occurs when the colliding objects "stick together." These are called *totally* inelastic collisions and are particularly easy to describe because the final velocity of the objects is *the same*. Again, since energy is lost in these collisions, only conservation of momentum (Equation 1) is applicable.

D. Procedure

Level the track. Weigh each of the carts, gratings and mass bars. Set the photogates so that they are near the center of the track. Since the light source in the photogate is a broad beam, best results are obtained with the grating a few mm from the detector side of the gate (*marked with a "D"*); however, be certain that both carts can pass through the photogates without hitting them.

Logger Pro determines a velocity by measuring the time that the light beam of the photogate is blocked by a black rectangle on the grating. The *Logger Pro* file that you will use has been set up with a default spacing of 1.0 cm, so you should set the height of the photogates so that the light is level with the 1-cm wide black rectangles.

Note that the carts are fitted with magnets on one end and Velcro on the other. Arrange the carts so that they interact through the magnets for elastic collisions and stick together with the Velcro for the inelastic collisions. To do this, you may have to lock down the spring that protrudes from one of the carts. Slide the spring *into* the body of the cart and then push it *up* slightly so that the groove on the spring bar engages the body of the cart and locks it in place. The small button above the bar pushes down on the bar and lets the spring supply a sudden impulse.

It is not possible in all cases for *Logger Pro* to record the motion of both carts both before and after a collision. If a cart stops before it passes through a photogate or moves so slowly that it doesn't reach the next photogate before the experiment ends, its motion won't be recorded. You should also note that the photogates can't determine in which direction a cart is moving. If the incident cart were to rebound from a collision with its initial speed, the recorded signal would be the same before and after the collision. You will have to determine the sign of each velocity from visual observation. It is important to record your observations, even if you cannot actually measure the speed of a cart.

Start *Logger Pro* and open the file *P:Logger Pro 3_Mech Labs\COL*. First check that your photogates are well calibrated relative to each other. Attach the two carts using their velcro sides and space the photogates as closely together as possible. Run the carts through the gates so that the readings from each photogate are alternated with those from the other. Record the average velocity for each photogate. (See the next page for how to measure the average velocity.) If the velocities read by the two photogates are different, note the ratio of the apparent velocities. Since the actual velocities must have been the same, this difference indicates an error in timing in one or the other photogate. Then set the photogates so that they are just a few cm more than two cart-lengths apart. For each of the 6 experiments, you will need to correct one of the velocities by this ratio.

Practice each experiment before taking data until you are confident about the procedure. Record one good data set for each of the six sets of conditions described below. Save every file separately, *e.g., dsa5col1, dsa5col2, etc.* You and your partner may share data sets for this experiment.

It is especially important that you keep good records with sketches and file names in your notebook for each part of this experiment. You may find it helpful to organize your data into a separate table for each interaction using column headings of *1*, *1′*, *2* and *2′*, and row headings of m, $\vec{v}$, $\vec{P}$, and K.

As you perform each experiment, use the following procedure to determine the velocities.

1. Identify in the velocity graph in *Logger Pro* a set of 3-5 data points that correspond to the velocity you wish to measure. You may wish to increase the size of this graph window to make the data points easier to see. You may also wish to rescale the y-axis (*right-click on the axis, change the scale to manual setting, and select the minimum and maximum values to plot; you probably should change back to autoscale before taking more data.*) Since the carts lose energy due to friction, select points that are close to the collision time.

2. Select these points directly on the velocity graph using the mouse and cursor. Position the mouse near the leftmost point, hold down the left mouse button while you slide the mouse to the rightmost point and then release the mouse button.

3. Let the computer calculate the average and standard deviation for the selected data points. Click on ANALYZE / STATISTICS and check the box for the quantity you wish to analyze. (*Do one of the velocities at a time*.) The standard deviation calculated by the computer is NOT the quantity you need to use directly for the estimated error in the velocity; to get this value (*the uncertainty in the mean*) you need to divide the standard deviation by the square root of the number of data points that you selected. (*See Appendix V on Uncertainties and Error Propagation for details*.) Note that *Logger Pro*, like *Origin*, does not handle significant digits properly. This is up to you to correct. Do not quote a result as: 0.58691 ± 0.00871 m/s, it should read 0.587 ± 0.009 m/s or at most 0.5869 ± 0.0087 m/s.

4. If you make a mistake and have to reselect data, you can delete the statistics results by clicking in the upper right-hand corner of the statistics box.

5. Record the velocities and uncertainties in your notebook and use the Save As command to save the data along with the statistical results.

6. Of the 6 experiments described below, print only the velocity graph (*with statistics boxes*) for the data for the second experiment, col2 (*collision #2*), and include this graph with your paper.

D.1. Elastic Collisions

Arrange the carts so that their magnets repel when they collide. Set a stationary target car just short of the photogate it will pass through after the collision. Give the incident cart a gentle push such that the carts do not actually bump, but interact through the repulsion of the magnets. Note that this collision via magnets takes some time (*or distance*) to complete; it is not instantaneous. This fact means that the first few data points collected by the target photogate and the last few collected by the first photogate may not show the carts at full speed. Ignore any points immediately before or after the collision if they appear to be anomalously low.

Record and save for analysis one good run under each of the following conditions.

(a) Use one iron bar on each cart.(*col1*)
(b) Use one bar on the incident cart, none on the target cart. (*col2*)
(c) Use one bar on the target cart, none on the incident cart. (*col3*) For this collision, you *must* record final velocities for both carts.

D.2. Inelastic Collisions—Energy Loss

Arrange the carts so that when they collide, the Velcro makes them stick together, *i.e.*, the collision is *totally inelastic*. Remember to reposition the gratings as necessary so that they are close to the detector side of the photogate. Use roughly equal masses, with one bar on each cart.

Give the incident cart a push so that it collides with the target cart and the two move together after the collision. Record a good set of data (*col4*).

D.3. Inelastic Collisions—Energy Gain (*explosion*)

One of your carts is fitted with a spring. Load that cart with an iron mass, and use a second cart without added mass. Arrange the two carts between the photogates with the spring fully compressed. Carefully release the spring by giving it a downward tap with a pen and record a good set of data (*col5*).

Repeat as above but with both carts unloaded (*col6*).

E. Analysis

For each experiment, use the velocity data in *Logger Pro* to calculate and tabulate as available the incident momentum $\left(\vec{P}_1\right)$ and kinetic energy (K_1), the final momenta $\left(\vec{P}_1' \text{ and } \vec{P}_2'\right)$ and kinetic energies (E_1' and E_2'). Calculate the total final momentum and kinetic energy.

To draw conclusions regarding the conservation laws you need to know the uncertainties in your measurements. Since a thorough error analysis of all six collisionsg would be fairly time consuming, you may perform a full error analysis to find the uncertainties in $\vec{\varepsilon}_P$ and ε_K for only one data set; use the measurements made in Section D.1.c (*elastic collision with weighted target and unweighted incident cart – col3*). Since the apparatus and velocities are similar in the various experiments, it is reasonable to assume that the errors you calculate are typical for the other measurements.

E.1. Elastic Collisions

E.1.a. Equal Masses

Note that, with 2 equal masses, the speed of the incident cart after the collision is predicted to be zero. Check that this is true by calculating $\vec{\varepsilon}_P = \frac{\Delta\vec{P}}{|\vec{P}_1|} = \frac{\vec{P}_2' - \vec{P}_1}{|\vec{P}_1|}$. Check conservation of kinetic energy by calculating $\varepsilon_K = \frac{\Delta K}{K_1} = \frac{K_2' - K_1}{K_1}$.

E.1.b Unequal Masses

If you were able to measure the velocity of both carts after the collision, check conservation of momentum and energy by calculating

$$\vec{\varepsilon}_P = \frac{\Delta\vec{P}}{|\vec{P}_1|} = \frac{\left(\vec{P}_1' + \vec{P}_2'\right) - \vec{P}_1}{|\vec{P}_1|} \qquad (5)$$

and

$$\varepsilon_K = \frac{\Delta K}{K_1} = \frac{\left(K_1' + K_2'\right) - K_1}{K_1} \qquad (6)$$

However, if you are missing one of the final velocities, then assume momentum is conserved and use momentum conservation to find the missing velocity. Then you will have enough information to at least check energy conservation. This is a valid procedure, often used in particle physics experiments where the momentum of a particle can't always be measured directly. In effect, you are assuming the validity of one conservation law to test the other.

E.2. Inelastic Collisions—Energy Loss

Check conservation of momentum and calculate the relative energy loss. Discuss where the energy goes.

E.3. Inelastic Collisions—Energy Gain (*explosion*)

Check momentum conservation in each experiment (*Equation 1 and 2 with incident* $P_I = K_I = 0$) and compare the final total kinetic energies in the two experiments.

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