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Magnetic Linear Accelerator

Physics Demonstration Kit

Catalog No. AP6838 Publication No. 6838

Introduction

Create a simple magnetic linear accelerator using magnets and steel ball bearings! Demonstrate magnetism, the conservation of energy and momentum, and projectile motion.

Science Concepts

- Potential vs. kinetic energy
- Magnetic potential energy
- Conservation of energy and momentum
- Projectile motion

Materials

Angled metal track, 75 cm*
Books, 2–3 (optional)
Neodymium magnets, 6*
Steel ball bearings, ⅝″ dia., 10*
Support feet, wood, 2*

**Materials included in kit.*

Safety Precautions

Use caution when handling the neodymium magnets. These magnets are very strong and may quickly snap together and pinch skin. The magnets are fragile and may shatter if dropped or if they hit another object too hard. Wear safety glasses when performing this demonstration.

Preparation

1. Place two neodymium magnets together in each of the three locations along the angled track, starting 10 cm from one end and spacing them 20 cm apart (see Figure 1). Make sure the north (or south) poles of the magnets point in the same direction along the track. The magnets will "stick" to the metal track and remain in place.

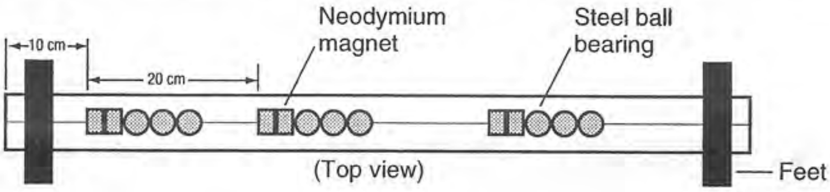

Figure 1.

2. Slide the support feet onto the metal track so that the angled metal track is in a V-position with the V pointing down (Figure 2).
3. Place three ⅝″ diameter steel ball bearings to the right of each magnet set.

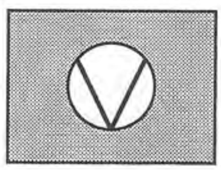

Figure 2.

Procedure

1. Position the last steel ball bearing to the left of the first set of magnets.
2. Slowly push the single ball toward the first magnet set. Once the ball is close enough to the magnet, it will be pulled towards the magnet.
3. Observe the "chain reaction" collision of the ball bearings as the small motion of the first ball is translated and enhanced in each successive collision.
4. The last ball in the chain will launch off the end of the track at a surprisingly fast speed. How far does the ball travel? Does it appear to be moving faster than the ball that initiated the collision?

Disposal

The materials can be reused indefinitely and should be saved for future use.

Tips

- The more ball bearings there are between the magnet and the launched ball, the more kinetic energy the launched ball will acquire. However, three to four balls seem to work the most efficiently. The fifth or sixth ball added to the system will not be attracted to the magnet significantly, and the overall dipole magnetism will no longer simply be proportional to $1/r^3$. The potential energy that the incoming ball gains as it travels from "infinity" to the surface of the magnet will be less, and thereby the resulting kinetic energy will be less.
- Neodymium magnets are strong and it may be difficult to separate the ball from the magnet. It may be easier to slide the steel ball bearings off the magnets, instead of pulling them directly.
- The magnets are fragile and may crack or chip if they are struck too hard by the ball bearings, or if they are dropped.
- Keep neodymium magnets away from computer disks or other magnetic strips such as credit cards. They will quickly erase the magnetized data.

Extensions

- Experiment with the number of magnets at each location, the number of steel ball bearings at each location, and the separation between the magnet systems. Attempt to arrange the components to create the "most powerful" linear accelerator.

  Optional Student Questions

  ➢ How does the spacing between the magnets affect the speed of the last steel ball bearing?

  ➢ Does the apparatus still "work" when only one ball bearing is placed next to the magnets, instead of three? Does the accelarator "work" when two ball bearings are next to the magnets? If so, do the launching ball bearings move faster or slower?

- Place a target, such as a large sheet of paper, on the floor and challenge student groups to shoot their ball towards the target. The group that shoots the ball closest to the center of the paper target wins. Students can experiment with the number of magnets, the spacing and the number of balls at each location to shoot a ball so that it stops on the target at a certain distance away. This experiment works best on a carpeted floor so the rolling ball will come to a stop in less than three meters. The ball may roll "forever" on a hard floor.
- Determine the speed of the ball by measuring the distance the ball travels through the air when the Magnetic Linear Accelerator is turned into a projectile launcher. Use two or three books to prop up one end of the track up at approximately a 20° angle. Make sure the track is supported securely and remains stable. Lay several sheets of carbon paper down in front of the launching track at a distance at least as far as the ball will travel. When the ball launches and lands on the carbon paper, it will leave a mark on the tabletop. Measure the distance the ball traveled from the end of the launching track. Use this distance and height of the launch track to calculate the initial launch speed of the ball. (Refer to your physics or physical science textbooks for the proper kinematics equations of motion. Remember, the ball bearings will have both linear and rotational motion.)

  ➢ Determine the "escape" velocity of a single-magnet system using the projectile launcher method. Then, determine the "escape" velocity of the last ball of a three-magnet system accelerator using the same method. Compare the two velocities to determine the amount of energy that was "gained" in the three-magnet system.

- Experiment with smaller ball bearings as the final "leaving" ball. Or, use a larger ball bearing as the initiating ball. Place a non-magnetic, such as a copper, aluminum, plastic, or glass ball (marble) at the end of a bearing system. Place the ball at different locations in the system to determine its effect.

Optional Student Questions

➢ How does the size of the ball bearing affect their speed?

➢ How does the accelerator respond when a nonmagnetic metal ball is used as the final leaving ball? How does it function when a nonmagnetic ball is placed at different location along the sequence?

Discussion

This demonstration may appear to break the laws of physics, especially the laws of conservation of energy and momentum, because the ball bearings appear to gain free energy after each collision. In reality, however, no laws have been violated. This is not a free-energy generator or perpetual motion machine. The key to this demonstration is the potential energy of the invisible magnetic fields. Magnetic fields store potential energy the same way that a spring does when stretched or that a ball does when it is held above the ground.

When the magnetizable metal ball is far away from the magnet (at "infinity"), the ball has a small amount of magnetic potential energy. This is similar to the gravitational potential of a ball held at a great distance above the Earth—the farther away from Earth, the lower its potential energy (where gravitational potential is proportional to the inverse of the distance between the objects). As the steel ball bearing is pulled toward the magnet, the ball bearing's speed increases tremendously over the short distance it travels. The ball then hits the magnet and comes to a stop. Since energy and momentum must be conserved in an elastic collision, the energy must be transferred through the solid magnetic system. The energy is transferred to the last ball at the end of the system of magnets and balls. The last ball in each magnet system is already a great distance away from the magnet so it does not require much energy to "break away" from the magnet's potential energy. The difference between the work done by the magnet on the incoming ball and the work necessary to break the final ball away from the magnet determines the amount of kinetic energy (and therefore speed) of the final ball in the sequence. A large amount of work is done on the incoming ball, and only a small amount of work is needed to break the launching ball away. Therefore, the kinetic energy of the final ball in each sequence will be very high and the ball shoots off with a high speed.

The same pattern repeats itself at the other magnet systems along the accelerator. However, the incoming ball at each subsequent magnet system already has a high initial speed. The final speed of the ball as it hits the magnet will be much higher than the speed of the original initiating ball. So, the second leaving ball will travel faster than the first leaving ball. The third leaving ball in the three-magnet system will travel even faster.

Mathematical Discussion (Advanced)

The force produced by a dipole magnet is proportional to the inverse cube of the distance away from the magnet ($1/r^3$). [As a comparison, the force of gravity is proportional to the inverse square of the distance ($1/r^2$)]. The inverse cube relationship is why the force of a magnet decreases so quickly with distance. Since the force of the magnet is proportional to $1/r^3$, the magnetic field's potential energy can be calculated (using calculus) to be proportional to $1/r^2$. [Again, for comparison, gravitational potential energy is proportional to $1/r$.]

For simplicity, assume the magnet is in the shape of a sphere. In order for a small magnetic object to escape from the surface of another magnetic object and travel to infinity, the amount of energy (work) put into the object must be equal to the magnetic potential at the surface of the magnet. That is, the work put into the object must be proportional to $1/R^2$, where R is the radius of the magnet.

The incoming steel ball approaches the magnet from "infinity." When it "lands on" the surface of the magnet, the ball's potential energy is proportional to $1/(2R)^2$, or

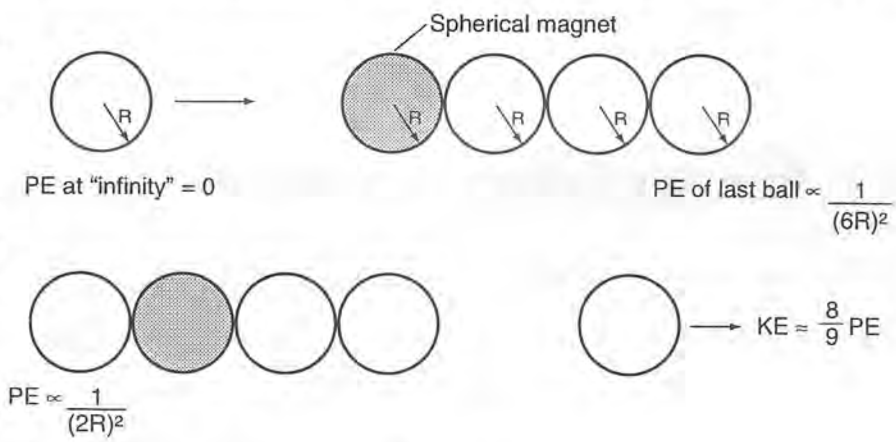

Figure 2.

$1/4R^2$ (measuring from the center of the mass). The center of the last ball in the chain is $5R$ away from the surface of the magnet. The magnetic potential energy of this ball is proportional to $1/(R+5R)^2$, or $1/36R^2$. Therefore, the last ball in the series needs only one-ninth the energy supplied by the incoming ball in order to "escape" the magnet. The remaining eight-ninths of the energy provided by the incoming ball becomes kinetic energy for the leaving ball. The kinetic energy, and therefore the velocity of the ball will be large as it leaves the magnet system. However, it will actually be less than the incoming ball's kinetic energy just before it struck the magnet.

Assuming there are no energy losses, the first leaving ball approaches the next magnetic system with 8/9ths of the original ball's energy. This ball then imparts 8/9ths of the energy it gains by approaching the magnet from infinity plus the 8/9ths of the original energy. So, the second leaving ball will have 16/9ths of the energy compared to the original initiating ball. The second ball will have nearly double the amount of energy the original ball transferred. The cycle continues with the third set of ball bearings. The final ball bearing will have approximately two and two-thirds times the energy supplied by the initiating ball. Of course, energy is dissipated as heat and sound, so the true energy and speeds do not approach these theoretical values. Also, the ball bearings will have both rotational and kinetic energy since the balls roll. Therefore, the linear speed of the ball will be lower than expected compared to a non-rolling object.

Demonstration Worksheet Answers *(Student answers will vary.)*

1. Draw the setup of the linear magnetic accelerator. Describe the sequence of the ball interactions. What type of collision(s) does the ball bearings and magnets experience? Do the balls appear to have more or less speed after each collision?

   The first ball is pushed toward the first magnet set by a finger and then is pulled toward the magnet very quickly. The ball hits the first magnet and stops, and the last ball in the series shoots off toward the next magnet system. The last ball appears to have more speed than the original ball. The magnet and the other two balls in the first position do not move. The collision appears to be an elastic collision because when the ball hits the magnet and stops, the last ball in the series is knocked away. When this ball hits the second magnet system, the pattern repeats itself. The third ball then hits the third magnet and the fourth ball bearing shoots off with great speed. The entire sequence occurs very quickly.

2. What force moves the ball bearings along the track?

   The magnet pulls on the metal ball so it must be a magnetic force that pulls the ball bearing.

3. Does the final ball have more speed than the original ball? If so, develop a hypothesis to explain how this is this possible.

   The final ball does appear to travel at a much higher speed compared to the original ball bearing that hit the first magnet.

   The magnetic force adds speed to the ball when it is pulled toward the magnet. Therefore, each magnet in the sequence adds speed to the ball. After three magnet collisions, the last ball will have more speed than the first ball.

Connecting to the National Standards

This laboratory activity relates to the following National Science Education Standards (1996):

Unifying Concepts and Process: Grades K–12
Evidence, models, and exploration
Content Standards: Grades 5–8
Content Standard A: Science as Inquiry
Content Standard B: Physical Science, understanding of motions and forces, transfer of energy.
Content Standards: Grades 9–12
Content Standard A: Science as Inquiry
Content Standard B: Physical Science, motions and forces, conservation of energy, interactions of energy and matter.

Reference

http://my.execpc.com/~rhoadley/magInch.htm (accessed 7-1-04)

The *Magnetic Linear Accelerator—Physics Demonstration Kit* is available from Flinn Scientific, Inc.

Catalog No.	Description	Price/Each
AP6838	Magnetic Linear Accelerator—Physics Demonstration Kit	Consult Your Current *Flinn Catalog/Reference Manual.*

Name: ______________________

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