Energy and Momentum in the Gauss Accelerator

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James Rabchuk's recent paper[1] describes a method for measuring the kinetic energy changes in the Gauss accelerator, as well as a calculation of the change in potential energy. In this paper, a simple method for measuring both the change in potential energy and the change in kinetic energy will be presented. The measurements can be made with rulers, strings, and weights. In the process, your students will learn about the relationship between work and potential energy as well as the law of conservation of energy. Issues associated with the law of conservation of momentum in the accelerator will also be addressed.

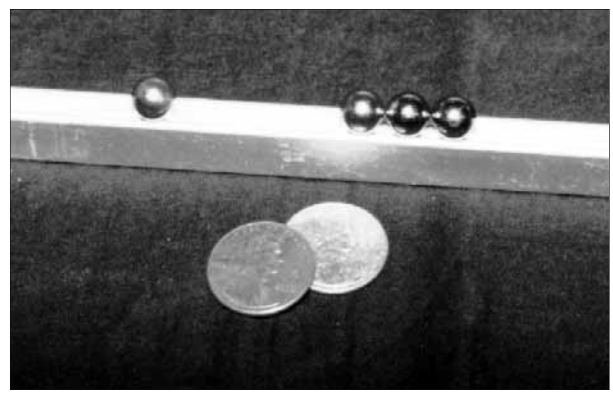

Fig. 1. The Gauss accelerator ready to delight and amaze.

The Gauss accelerator[2] pictured in Fig. 1 consists of an 8-mm diameter spherical neodymium magnet[3] and three 5/16-in (0.313-in) steel ball bearings. The device is available with cube- shaped magnets from Science Toys.[4] I first saw the Gauss accelerator in a much larger version presented to a local AAPT meeting at the Exploratorium, by Paul Doherty of the Teacher Institute.

When the lone ball on the left is gently brought in toward the right [Fig. 2(a)], it accelerates until it collides with the magnet. The result is that the incoming ball sticks to the magnet, and the ball on the right takes off with a surprisingly large velocity [Fig. 2(b)].

Where Does the Energy Come From?

Since the outgoing ball is moving faster than the incoming ball, the kinetic energy of the system has increased. According to the law of conservation of energy, the potential energy of the system must have de-

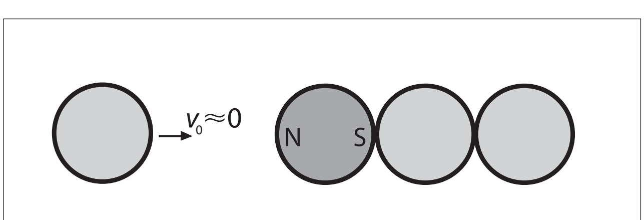

Fig. 2(a). The incoming sphere is moving at a low speed.

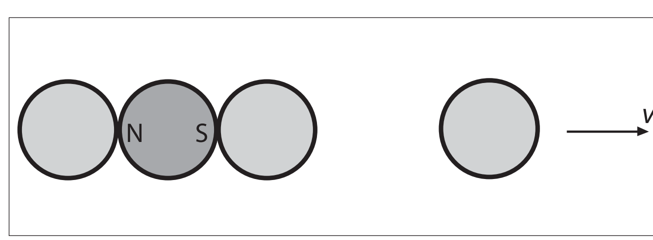

Fig. 2(b). The outgoing sphere is moving with a much higher speed.

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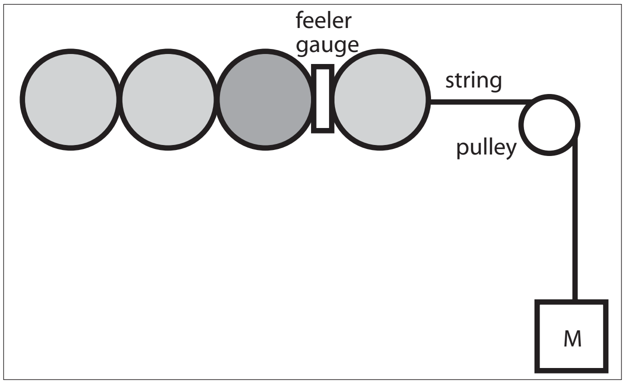

Fig. 3. Hanging weights are used to measure the force exerted by the magnet. The distance is varied by changing the thickness of the feeler gauge.

creased. The potential energy that drops is associated with the magnetic field. You can get a sense of where the energy comes from as you set up the experiment. As you position the ball bearings, the outgoing ball feels much less magnetic attraction than the incoming ball. If you set up the experiment in the right frame of mind, you can get the sense that you are storing energy in the system just as you would by setting a mousetrap. The energy involved can be quantified to an extent by conducting some basic measurements.

The change in potential energy can be found from the difference between the work done by the magnet on the outgoing ball and the work done on the incoming ball. The work done requires estimates of the magnetic force as a function of distance. This can be accomplished by gluing a string to one of the balls, running the string over a pulley, and using hanging weights to balance the magnetic attraction at different distances as shown in Fig. 3. A nonmagnetic "feeler gauge" can be used to measure distance.[5] The force versus center-to-center distance curves are shown in Fig. 4. The strength of the magnet is impressive; it can support the weight of a 600-g mass (5.8 N = 1.3 lb). The work done is equal to the area under these curves. The results are roughly

$$W_{in} = 5.9 \text{ mJ} \quad \text{and} \quad W_{out} = 0.3 \text{ mJ}.$$

The net work done yields an estimate of the change in potential energy,

$$\Delta U = W_{in} - W_{out} \approx 5.6 \text{ mJ}.$$

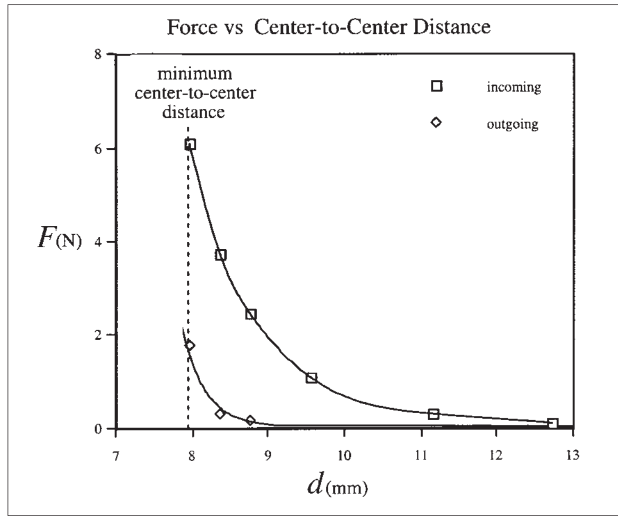

Fig. 4. The force versus center-to-center distance curves for the incoming and outgoing balls can be used to estimate the work done.

The increase in kinetic energy can be found by measuring the mass of the balls (m = 2.0 g) as well as the incoming and outgoing speeds. Since the incoming ball is brought in very slowly (until the magnetic force starts attracting it), it is safe to assume the initial speed is zero. The final speed can be found by allowing the ball to fly horizontally off a tabletop of height h while measuring the range of the projectile R. Care must be taken not to allow the ball to rotate after the collision so that none of the mechanical energy will be converted into rotational kinetic energy by friction with the table. This was attempted by putting the Gauss accelerator as close to the edge of the table as possible. The resulting increase in kinetic energy is

$$\Delta K = \frac{1}{2}mv^2 = \frac{1}{2}m\frac{gR^2}{2h}.$$

In this case, h = 0.78 m and R = 0.83 m, giving a change in kinetic energy of roughly

$$\Delta K \approx 4.3 \text{ mJ}.$$

Presumably, the 1.3 mJ of lost mechanical energy can be explained by the rotational kinetic energy of the incoming ball being lost to friction, inelastic behavior of the colliding spheres, ohmic heating due to induced eddy currents, and other nonconservative losses.

A Comment Regarding Momentum

When this experiment is conducted on a smooth surface, the recoil of the magnet and two balls is fairly easy to see and establishes the idea that the conservation of momentum is working. However, on a rough surface no recoil is evident. Momentum is clearly not conserved. This is due to the external force of friction acting on the system during the collision.

Some Extension Activities

You can have more fun with the Gauss accelerator by adding multiple stages (like the commercial device[3]). Try studying the effect of more ball bearings on either side of the magnet. More magnets can also be added. Get a straw and try the energy experiments vertically against gravity. Only a physics person can have so much fun with such a simple device!

References

1. J. Rabchuk, "The Gauss rifle and magnetic energy," *Phys. Teach.* **41**, 158–161 (March 2003).
2. This device is also known as the Gauss rifle. However, due to the high rate of gun violence in our schools, I choose to call it the Gauss accelerator.
3. The idea of using spherical magnets came about because part of the magical properties of the Newton's cradle device is often attributed to the spherical shape of the colliding spheres. For example, see A. David, "Colliding rods: Dynamics and relevance to colliding balls," *Am. J. Phys.* **62**, 522–525 (1994).
4. Science Toys (http://www.scitoys.com/scitoys/scitoys/magnets/gauss.html) sells a kit with cube-shaped magnets for $26. Spherical neodymium magnets can be obtained fairly cheaply from Educational Innovations Inc.; 888-912-7474 or http://www.teachersource.com.
5. Thin brass strips of known thickness (1/64 in, 1/32 in, and 1/16 in) were used. They were found at a local hardware store and were very inexpensive.

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