JOURNAL OF CHEMICAL EDUCATION

Cite This: *J. Chem. Educ.* 2019, 96, 100−103

Laboratory Experiment

pubs.acs.org/jchemeduc

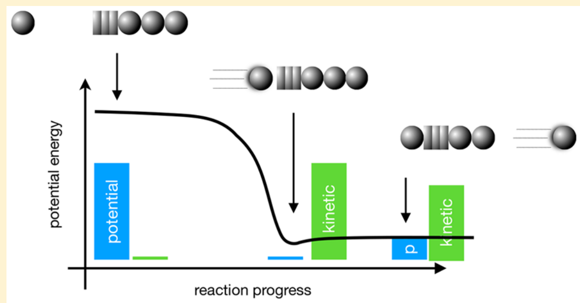
Modeling Chemical Reactions with the Gaussian Gun

Leslie Atkins Elliott,* Elizabeth Sippola, and Jeffrey Watkins

Department of Curriculum, Instruction & Foundational Studies, Boise State University, 1910 W. University Drive, Boise, Idaho 83725, United States

Supporting Information

ABSTRACT: In this article, we describe how the Gaussian Gun, a simple configuration of magnets and ball bearings, can be leveraged to connect ideas from physics to representations and ideas that are central to chemistry and challenging for students to learn. In particular, we show how the Gaussian Gun, an arrangement of ball bearings and magnets, models much of the physics behind chemical bonds and exothermic reactions, and develops students' understanding of reaction maps.



KEYWORDS: *First-Year Undergraduate/General, Interdisciplinary/Multidisciplinary, Analogies/Transfer, Hands-On Learning/Manipulatives, Reactions, Reactive Intermediates*

Introductory physics is, for most students, not an end in itself, but a required course, as students pursue other scientific and technical majors. Ideally, the topics from introductory physics will be useful for students in their other majors; however, we know that physics courses which do not explicitly attend to connections to other disciplines will have low instances of transfer to those disciplines.[1] In this article we describe an activity in which the ideas of force, work, and energy can be used to model ideas related to chemical reactions.

In particular, we describe how the Gaussian Gun (a simple arrangement of magnets and ball bearings that, when released, ejects a ball at high speed) can be used as a model for exothermic reactions in general, and a two-step reaction in chemistry in particular. In doing so, students have not only a stronger understanding of core chemistry concepts and representations, but also a stronger understanding of the role that physics plays in chemistry. We begin below with a brief description of the physics behind the Gaussian Gun, followed by a discussion of its connections to exothermic reactions, and a description of an activity to help students connect these two ideas. We then offer additional connections and directions that the instructor may pursue, including a connection to activation energy and to reactive intermediates. We do so to broadly introduce this apparatus as a generative context for student inquiry into reactions, relevant to a range of courses. In the Supporting Information we offer an activity, in which students map out a reaction diagram, with support for instructors.

Versions of a Gaussian Gun activity have been used in an undergraduate introductory physics courses for life science majors[2] as part of a homework assignment. It has also been used as a context of inquiry for secondary teachers participating in the Energy Project professional development program.[3] Finally, it has been further developed in a range of courses for preservice and in-service high school science teachers as they grapple with the "crosscutting concept" of energy.[4,5] We expect it will also be useful for students in chemistry courses who have had traditional physics preparation.

MODELING REACTIONS WITH THE GAUSSIAN GUN

Physics of the Gaussian Gun

A Gaussian Gun is a simple arrangement of ball bearings and strong disc magnets,[6] as shown at the top of Figure 1. When ball A is released, it accelerates toward the magnet, and strikes it, and ball D is ejected at great speed. The sudden appearance of kinetic energy is surprising and offers a rich context for exploring potential energy; this serves as a model for the production of thermal energy in exothermic reactions. While computer-based simulators (e.g., the Molecular Workbench[7])

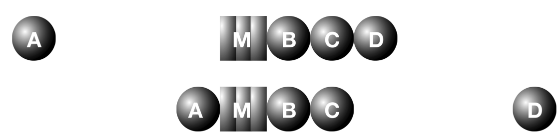


Figure 1. Initial (top) and final (bottom) configurations of the Gaussian Gun. The circles A−D represent ball bearings (ferromagnetic); the rectangles represent strong disc magnets. Ball A is not initially in motion in the top panel; ball D is in motion in the bottom panel.

Received: August 31, 2018
Revised: November 13, 2018
Published: December 3, 2018

also offer simulations of exothermic reactions, we find that having this tangible physical model provides a productive analogue for bonding, potential energy, and the nature of exothermic reactions. This model can be investigated experimentally in a way that simulators often cannot offer students. In addition, as Wu, Krajcik, and Soloway[8] note with regard to chemical reactions (p 822), "[symbolic] representations are invisible and abstract while students' thinking relies heavily on sensory information."

A simple analysis of the system as a whole (the four balls and magnet) will lead to the recognition that the initial configuration must have more potential energy than the final configuration. However, a finer-grained analysis, considering separate elements of the system, is necessary to understand why there was such a great deal of potential energy to begin with. To provide a brief explanation for the appearance of kinetic energy, we can compare the configuration at the beginning and end of the interaction (see Figure 1). At the top is the initial configuration (referred to below as A + MBCD), and at the bottom the final (AMBC + D). In the top configuration, the balls are, on average, farther from the magnet. As with any attractive force, the farther apart the interacting objects are, the more potential energy there is in the system. It is this difference in potential energy that is converted to the kinetic energy of the ejected ball. The force rises precipitously as the ball approaches the magnet, yet it is almost imperceptible at just a few ball-lengths from the magnet. Thus, the kinetic energy that ball D receives is enough for the ball to "escape" the attraction from the magnet.

Gaussian Gun as a Model for Reactions

We use this system as a model for exothermic reactions. While there are, of course, numerous ways in which the analogy is incomplete (e.g., these are magnetic, not electric, interactions; there are none of the energy level or spatial constraints that atoms and molecules have etc.), we find the following ideas particularly useful in modeling chemical reactions.

- It models the way in which a "bond" is not a tangible object, but a statement of the stability of two attracting objects, with ball A "unbound" initially[9] and ball D "breaking" its bond after the impact of A; this addresses an idea known to be challenging for introductory students.[10]
- Kinetic energy is produced when a bond is formed (when ball A gets pulled in to the magnet), and since kinetic energy is readily transferred between objects (a consequence of the work-energy theorem), we describe kinetic energy as energy that has been "released": it is no longer bound up in untransferrable potential energy. The notion that forming bonds releases energy is challenging for students.[11]
- Similarly, and similarly confusing,[11] energy is required to break a bond (when you forcibly pull a ball away, or when ball D is knocked away by the transfer of energy from an incoming ball).
- Exothermic reactions are ones that release energy, and since this reaction releases energy, the reactants (here, AMBC + D, top of Figure 1) must have more potential energy than the products (A + MBCD, bottom of Figure 1).

The above ideas are ones we introduce, and sometimes resolve, through class conversations and debates as students explore the materials and discuss where the final energy comes from. If not resolved in the initial conversations, these ideas should be resolved by the end of the activity.

Among the more challenging ideas raised in our discussions is the difference between the very tangible feeling of force, which gets stronger as you come close to the magnet, with the abstract idea of energy, which increases in this scenario even as the force is decreasing. To develop this idea further, we have students construct a reaction diagram by first measuring the force experienced by balls A and D, and then calculating the energy from this. This representation not only supports understanding the energy in the scenario but also serves to introduce students to reaction diagrams, as described in the following section.

Reaction Diagramming

Reaction diagrams map the potential energy of a system undergoing a reaction; the potential energy is represented on the y-axis as the reaction progresses. That progression is represented on the x-axis. In chemical scenarios, we do not, of course, directly measure the energy for a single set of reactants; determining a reaction diagram generally involves moles of reactants and a measurement of the heat that is absorbed or released. From this we can infer the potential energy of the system.

In this system with a magnet and balls, which serves as a limited model of a single set of reactants, we can measure the energy of the single "reaction" by calculating the work done on the system as a ball is moved in and the other ball is moved out (this approach is a physical analogue to the chemical approach taken in Gillespie, Spencer, and Moog).[12] That is, students can measure the force that ball A experiences as it is drawn to the magnet and, knowing the distance it travels, calculate the work done. Similarly, by measuring the force that ball D experiences as it gets pulled away from the magnet, we can calculate the work done to eject ball D from the system. Ignoring friction,[13] we can infer that the work done is equal to the change in potential energy and develop a reaction diagram from this data. The steps to do this are described below. Note that while students do take numerical data, our goal for this lab is more conceptual than calculational: it is not the numbers, *per se*, but the shape of the graph that we find instructive.

To measure the force, a simple Pasco force probe was used (most physics departments will have this or a similar instrument for their undergraduate laboratories), together with a meter stick and the Gaussian Gun (4 ball bearings and a set of strong magnets). The setup is shown in Figure 2. The

Figure 2. Set-up for measuring the force on a ball. A loop is strung around or glued to the ball, which is then attached to a force probe. A ruler is used to measure distance.

center of the magnet is taped down at the center of the meter stick; a string is tied and/or glued to one ball, and this string is attached to the force probe. Further details on measurements are in the lab guide, available in the Supporting Information.

From this data, generating a plot of the potential energy in the system as the "reaction" progresses is a simple calculation, though in our experience, this requires a class discussion to be meaningful. A spreadsheet (a template is available through the Supporting Information) may be provided to generate the

DOI: 10.1021/acs.jchemed.8b00709
J. Chem. Educ. 2019, 96, 100−103

graph shown in Figure 3; however, we encourage students to generate this on their own depending on the skills of the class.

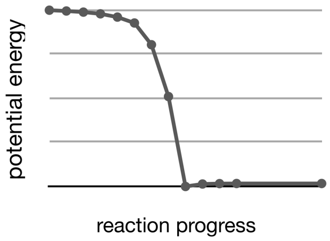


Figure 3. Reaction diagram for the Gaussian Gun.

The features of the graph to notice, some of which relate to common topics in introductory physics (P) and some of which are features that, while the ideas are from physics, are more significant to chemistry (C), include the following:

- a strong force is represented by a steep curve, a weak force by a relatively flat curve (P);
- the force, represented by the slope of the graph of potential energy, is clearly strongest on ball A when it is closest to the magnet; this is consistent with our experience in trying to pull ball A from the magnet (P);
- to move ball A from the origin (0) away from the magnet requires a lot of energy (P); similarly, when ball A moves toward the magnet it will gain a lot of kinetic energy (P);
- ball D does not experience a strong force, and the energy required to move ball D from its origin requires a minimal amount of energy (P);
- the amount of energy that ball A gains, and then transfers to ball D, is far greater than is needed for ball D to roll away from the magnet (C);
- the difference between the PE of ball A at its starting point and the PE of ball D at its ending point is the amount of energy gained by ball D (C);
- while the ball/magnet model shows a clear increase in kinetic energy, in analogous chemical systems this would be detected as an increase in temperature (for an adiabatic exothermic reaction) (C).

The above are all part of our lab activity (available in Supporting Information). However, this sets students up for further conversations, as described below.

We can now compare a generic "single step" chemical reaction diagram (Figure 4, left), to this system (Figure 4, right).

There are a few notable differences: (1) in the magnet system, there is no activation energy represented: the incoming ball (ball A) is not bound to another object, nor does it feel any shielding from the MBCD "molecule." This suggests that there is no "transition" state to reach before the reaction proceeds for the magnet. (2) There is a "dip" in the magnet system not present in the single step chemical reaction diagram. This suggests that there is a *reactive intermediate*, a state between A + MBCD and AMBC + D, that is stable. These are discussed briefly below.

Activation Energy

The reaction diagram in Figure 3 depicts the energy in the system due to the attractive interactions between the magnet and the balls. It would appear from the diagram that Ball A should not need any energy input to be drawn in to the magnet. The balls feel not only a force of attraction, but also a friction force that opposes that attraction which is not depicted on this graph, as friction does not store potential energy. In a nanoscopic chemical system, the reactants will also feel attractive forces that draw them into the reaction and opposing forces that prevent the reaction from proceeding. These interactions, which store potential energy, give rise to an activation energy.

To model this, a series of "MBCD" magnet/balls can be set up, as shown in Figure 5. To start the initial reaction, D must

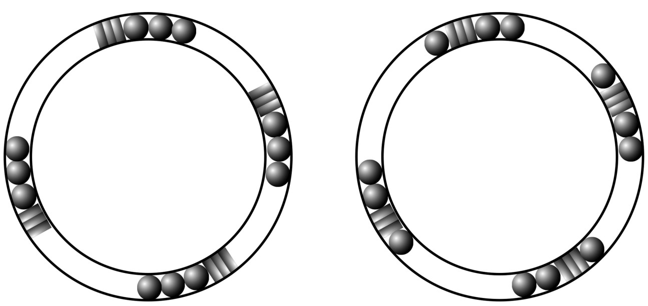


Figure 5. Series of Gaussian Gun reactions to model activation energy. At left is the initial state: a ball must be pulled far enough away to be attracted to the next magnet and begin the reaction. At right is the final, lower energy state.

be pulled away from a magnet system. This input of energy is the activation energy for the reaction. In addition, the ball must be pulled far enough away to be attracted to the next sequence of magnet and balls. The point when it is attracted to the next

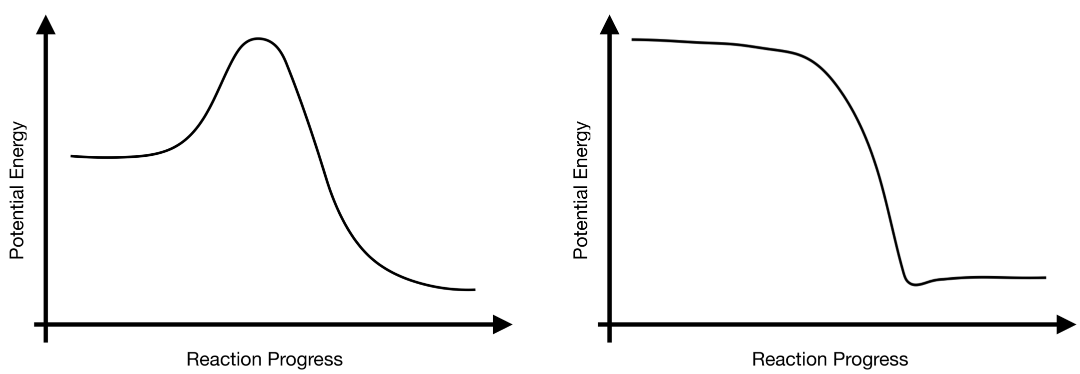


Figure 4. Generic reaction diagram (left) and one for the Gaussian Gun (right).

DOI: 10.1021/acs.jchemed.8b00709
J. Chem. Educ. 2019, 96, 100−103

"molecule" is referred to in chemistry as the transition state (see Figure 4).

Reactive Intermediates

Reaction diagrams can represent reactions that have multiple steps, as happens when the products of one reaction are used as reactants for an immediately following reaction. In a multistep reaction diagram, each peak represents a transition state: something that theoretically exists, but is too unstable to isolate in the real world. Physics describes these peaks as metastable. In the valleys of multistep reactions exist reaction intermediates: configurations that can stably exist, but due to the energetics of the prior reaction are not realized in this model since enough energy is present to immediately transition to the next step. It is particularly difficult for students to conceptualize transition states, as they cannot be isolated during the reaction.

In the Gaussian Gun reaction diagram (Figure 3), we can see a "dip" indicative of a reaction intermediate. This corresponds with the moment when all the interacting parts are bound: "AMBDC". The stability of such a "molecule" is clear: We can set up this configuration of the magnet and balls, and it will not move. However, during the reaction such a state exists only as long as it takes for the energy to transfer through the system, which is unobservably fast.

■ HAZARDS AND SAFETY PRECAUTIONS

All materials in this lab are models of chemical systems; no chemicals are used. Standard safety precautions for introductory physics, then, are indicated. In particular, depending on the strength and number of magnets used, the final ball can be ejected very quickly. Do not stand in the path of ball D. Wearing safety goggles can protect eyes from these projectiles. We have found that standard neodymium magnets, 1/2 in. in diameter and 1/8 in. wide, are sufficiently strong to produce the desired effect without ejecting a ball so quickly that it does damage.

■ CONCLUSION

While chemistry students are often required to take physics classes, connections between forces, kinetic energy, (chemical) potential energy, and chemical reactions are rarely addressed explicitly. In addition, students rarely have a strong visual model of energy transfers and transformations taking place at the atomic level. We have described a lab activity that uses a physical model for chemical reactions that supports students in making these connections.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.8b00709.

Notes for instructors and overview of the lab (PDF, DOCX)

Handout for students to do the lab activity (PDF, DOCX)

Spreadsheet to aid in recording and graphing data (XLSX)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: leslieatkins@boisestate.edu.

ORCID

Leslie Atkins Elliott: 0000-0003-4535-7348

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This material was developed in a research course for future teachers; we thank our fellow students, André Bolliou, Luke Bosse, Drew Daarud, Brittany Ferguson, Allie Howell, Hanna Irving, and Douglas Jackson. This work is sponsored by NSF grant 1712051.

■ REFERENCES

(1) Redish, E. F.; Hammer, D. Reinventing college physics for biologists: Explicating an epistemological curriculum. *Am. J. Phys.* **2009**, *77*, 629−642.

(2) Dreyfus, B. W.; Gouvea, J.; Geller, B. D.; Sawtelle, V.; Turpen, C.; Redish, E. F. Chemical energy in an introductory physics course for the life sciences. *Am. J. Phys.* **2014**, *82*, 403−411.

(3) Scherr, R. E.; Close, H. G.; Close, E. W.; Flood, V. J.; McKagan, S. B.; Robertson, A. D.; Vokos, S.; et al. Negotiating energy dynamics through embodied action in a materially structured environment. *Phys. Rev. Phys. Ed. Res.* **2013**, *9*, 020105.

(4) Atkins, L. J.; Erstad, C.; Gudeman, P.; McGowan, J.; Mulhern, K.; Prader, K.; Timmons, A.; et al. Animating energy: Stop-motion animation and energy tracking representations. *Phys. Teach.* **2014**, *52*, 152−156.

(5) Atkins, L. J.; Frank, B. W. Examining the products of responsive inquiry. In *Responsive Teaching in Science and Mathematics*; Robertson, A. D., Scherr, R., Hammer, D., Eds.; Routledge: New York, 2015; pp 56−84.

(6) Videos are widely available online: e.g., https://www.youtube.com/watch?v=LV4P7T76mDQ (accessed Nov 12, 2018).

(7) Xie, Q.; Tinker, R. Molecular dynamics simulations of chemical reactions for use in education. *J. Chem. Educ.* **2006**, *83*, 77.

(8) Wu, H.-K.; Krajcik, J. S.; Soloway, E. Promoting understanding of chemical representations: Students' use of a visualization tool in the classroom. *J. Res. Sci. Teach.* **2001**, *38*, 821−842.

(9) The graph generated suggests A should be bound, but friction prevents it from being drawn in.

(10) Özmen, H. Some student misconceptions in chemistry: A literature review of chemical bonding. *J. Sci. Educ. Technol.* **2004**, *13*, 147−159.

(11) Galley, W. C. Exothermic bond breaking: A persistent misconception. *J. Chem. Educ.* **2004**, *81*, 523.

(12) Gillespie, R. J.; Spencer, J. N.; Moog, R. S. An Approach to Reaction Thermodynamics through Enthalpies, Entropies, and Free Energies of Atomization. *J. Chem. Educ.* **1996**, *73*, 631.

(13) Including friction is straightforward: simply use a force probe to measure friction that the ball feels with the surface as it moves at a constant speed, and subtract that force from the total force you read by the magnet. However, we have found this to be negligible, and students rarely ask or are concerned about the role of friction at this point.

DOI: 10.1021/acs.jchemed.8b00709
J. Chem. Educ. 2019, 96, 100−103