SECTION 9

Nuclear Fission and Fusion: Breaking Up Is Hard to Do

Section Overview

Students calculate the binding energy of elements assigned to them individually and combine their data with the class to plot a graph of the average binding energy per nucleon versus the atomic mass (number of nucleons) for selected elements of the periodic table. They use the graph to interpret which elements have the most tightly bound nucleons and how the binding energy per nucleons increases if two light nuclei are put together or one heavy nucleus is broken down into two smaller nuclei. Students use examples of the binding energy per nucleon of nitrogen and oxygen having less binding energy per nucleon than the phosphorus nucleus that would be formed if these two nuclei fused. The example of Uranium breaking apart into lighter nuclei is offered as an example to explain the process of fission. They also study the chain reaction fission process using the model of a mousetrap and learn about chain reactions in the context of nuclear technologies.

Background Information

If the average binding energy of nucleons were to increase, additional energy would be released. This is the basis for the release of nuclear energy. The increase in average binding energy of nucleons can occur when small nuclei fuse or when large nuclei break into two pieces (fission). The binding energy curve of all of the elements has a peak at iron-57. This element has the greatest average binding energy per nucleon and is therefore the most stable element. Removing a nucleon (proton or neutron) or absorbing a nucleon would both result in a decrease of the average binding energy per nucleon. This would mean that energy must be supplied for this to occur. Uranium-235 becomes unstable after it absorbs a neutron.

When the uranium undergoes fission and becomes two lighter elements, there is a release of additional neutrons. These additional neutrons can then be absorbed by other uranium nuclei to induce fissions and the process can quickly become a chain reaction. This is what physicists realized could be the basis for an uncontrolled chain reaction – the first atomic bomb. By controlling the number of neutrons available for inducing fissions, the chain reaction can be controlled. In this way, you can have nuclear power plants.

The “curve of binding energy” shows a maximum at iron-57. It is the most stable nucleus in the sense that it has the greatest binding energy per nucleon. It takes more energy per nucleon to disassemble iron-57 than any other nucleus. That’s why both fission of uranium and plutonium, and the fusion of hydrogen, can liberate energy. However, fusion requires very high temperatures for the nuclei to overcome their electric repulsion and “overlap” or fuse. Without nuclear fusion in the core of the Sun, life would not be possible on Earth. All processes on Earth ultimately trace their sequence of energy transformations back to nuclear reactions in stars.

Crucial Physics

- The binding energy of a nucleus varies with the atomic number of the nucleus.
- A plot of nuclear binding energy per particle vs. atomic number gives a curve with a maximum near the atomic number of iron. Atoms with atomic numbers lower or higher than iron have less binding energy per particle. Iron is the most stable element in the universe.
- Atoms with an atomic number greater than iron may release energy and become more stable by undergoing fission to form lighter nuclei.
- Atoms with an atomic number less than iron may release energy and become stable by undergoing the process or fusion to form heavier nuclei.
- During the fission process of some elements, extra neutrons are released that serve as an inducing agent for other fissions, leading to a chain reaction.

Learning Outcomes	Location in the Section	Evidence of Understanding
Construct a graph of average binding energy per nucleon versus the number of nucleons.	***Investigate*** Steps 1 and 2	Students use combined class data to plot a graph of the binding energy per nucleon versus the number nucleons for each element on the periodic table, and then copy a graph for average binding energy per nucleon for selected elements from the chart provided in the text.
Infer the relative stability of different nuclear species by interpreting graphs.	***Investigate*** Steps 3–5	Students infer from the graphs of nuclear binding energy that binding energy per nucleon is a measure of nuclear stability. The binding energy per nucleon is greatest for iron and is less for elements of higher and lower atomic numbers.
Explain how a fusion reaction can release energy.	***Investigate*** Step 4 ***Physics Talk***	Students explain binding energy per nucleon increases when two small nuclei are put together to form one larger nucleus for elements of low atomic number. Energy is released in this process.
Explain how a fission reaction can release energy.	***Investigate*** Step 5	Students estimate the average binding energy per nucleon of barium-137 and krypton-84 to infer that the smaller nuclei have more binding energy per nucleon than uranium-235. This indicates that energy is given off. Students explain this phenomenon of nuclear fission using an equation that shows the release of three neutrons.
Describe a mousetrap model for a fission chain reaction.	***Investigate*** Steps 8 and 9	Students use the model of a mousetrap to show how many marbles are released in 20 cycles. They compare the chain reaction to the nuclear fission of Uranium.

Section 9 Materials, Preparation, and Safety

Materials and Equipment

PLAN A

Materials and Equipment	Group (4 students)	Class
Paper, graph, pkg. of 50		1 per class

Time Requirement

- Allow one class period or 45 minutes for the students to complete the *Investigate* portion of this section.

Teacher Preparation

- Prepare a list of students in pairs with each pair assigned to do the calculations for a particular element in the table in the *Investigate, Step 1* of the *Student Edition*. Assign the stronger pairs with elements with larger atomic numbers.
- Ensure that the calculations are done on the majority of the elements in the table *Investigate,* covering the entire range of elements.
- Search the Internet to find a Web site that has an animation of nuclear fission and nuclear fusion that can be shown to the students.

Safety Requirements

- There are no particular safety requirements for this activity.

Materials and Equipment

PLAN B

Materials and Equipment	Group (4 students)	Class
Paper, graph, pkg. of 50		1 per class

Time Requirement

- Allow one class period or 45 minutes to do the *Investigate* portion of this section as a teacher-led discussion, as well as the *Physics Talk* and other parts of the section in the *Pacing Guide*.

Teacher Preparation

- Prepare a list of students in pairs with each pair assigned to do the calculations for a particular element in the table in the *Investigate, Step 1* of the *Student Edition*. Assign the stronger pairs with elements with larger atomic numbers.
- Ensure that the calculations are done on the majority of the elements in the table in *Investigate, Step 1*, covering the entire range of elements.
- Prepare a Blackline Master found on the *Teacher Resources* CD to be used to graph the class data to develop the binding curve.
- Search the Internet to find a Web site that has an animation of nuclear fission and nuclear fusion that can be shown to the students.

Safety Requirements

- There are no particular safety requirements for this activity.

NOTES

Meeting the Needs of All Students

Differentiated Instruction: Augmentation and Accommodations

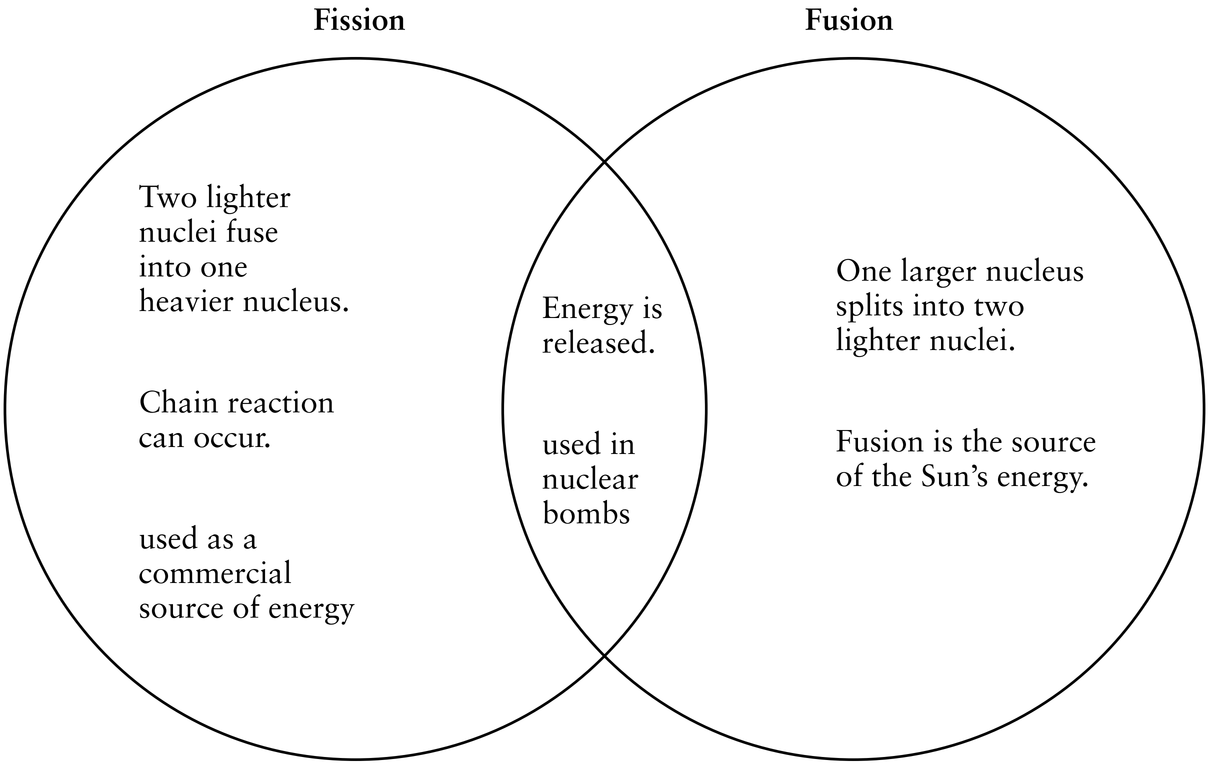
Learning Issue	Reference	Augmentation And Accommodations
Interpreting graphs	***Investigate*** Steps 2–8 ***Physics to Go*** Question 2	**Augmentation** • In order to answer questions about the binding energy graph, students must understand what the graph is showing them. After *Step 2* and *3*, facilitate a whole-group discussion to allow students to hear their classmates' interpretation of the graph. Some students will inevitably have different answers, and this discourse will encourage students to defend their reasoning by explaining themselves. By listening to student explanations, the teacher will understand student misconceptions, and other students will be gathering information to confirm or clarify their interpretations from the graph. As students continue through the *Investigate*, check in with the whole group periodically to allow groups to ask questions of the whole group. • If students are struggling to answer the questions in *Steps 2* and *3*, project the graph and talk about the important features of the graph and the data represented on the graph.
Understanding fusion and fission Reading comprehension	***Physics Talk*** ***Physics to Go*** Questions 3, 5, 8, 9, and 11	**Augmentation** • Ask students to create a two-column chart comparing fusion and fission. • Encourage students to use the Internet or other classroom sources to find more information that is not included in *Physics Talk*. This information can be used for the *Chapter Challenge*. **Accommodation** • Provide students with a copy of this section of the text. Instruct students to cut apart the text to divide into fusion and fission. Then students must rewrite the ideas in their own words.

Strategies for Students with Limited English-Language Proficiency

To help students understand political and social issues related to nuclear applications, divide students into three groups and assign each group one of the projects below. Be sure ELL students get writing and speaking experience during the course of the research and the presentation.

1. To help students focus on the presentation of their chapter project, assign them to design the museum exhibit in *Physics to Go, Question 7*. They can brainstorm ideas on what information to include in their museum exhibit, how to display the information, and how to incorporate the public's opinions and ideas. They should finish with a short presentation to the class.
2. Have students research the questions in *Physics to Go, Question 9*. Instruct them to find out as much as they can about fission as a source of energy and then write up a risk–benefit analysis of their findings. Have the group present its analysis to their community (the rest of the class), and then have the community vote on whether to allow use of nuclear fission energy in the town.
3. Because of the danger of an uncontrolled chain reaction in nuclear fission, fusion would be a much safer source of nuclear energy. As of now, however, scientists have not found a way to harness energy in this way. Have students address *Physics to Go, Question 8*, and present their findings to the class. How likely is it that fusion will one day be a feasible source of energy?

Venn diagrams are commonly used to compare and contrast. Ask students to create a Venn diagram to show similarities and differences between nuclear fusion and nuclear fission. Have them draw two intersecting circles and give them the labels "Fusion" and "Fission." Have them place similarities between the reaction types in the overlapping area, and characteristics that belong to only one category or the other in the appropriate circle. Students' diagrams may look like this:



Two lighter nuclei fuse into one heavier nucleus.

Chain reaction can occur.

used as a commercial source of energy

Energy is released.

used in nuclear bombs

One larger nucleus splits into two lighter nuclei.

Fusion is the source of the Sun's energy.

NOTES

SECTION 9

Teaching Suggestions and Sample Answers

What Do You See?

This illustration gives a clear indication that a chain reaction is taking place. Students might immediately link this scene to nuclear fusion or nuclear fission, as both processes are suggested in the title. Consider asking students why so many balls are being tossed up or what the dog did, or why is he now running away. These questions should get the class involved and energized in a constructive class discussion. As students respond, record the main highlights of the discussion on the board. Emphasize that carefully considered initial impressions are a gateway to a better understanding, and they will continue to investigate physics concepts using different learning techniques. Remind students that they will have other opportunities during this section to return to this illustration and appreciate the finer nuances of the physics concepts the artist is trying to convey.

What Do You Think?

Students will most likely be familiar with nuclear power and nuclear weapons. Initiate a discussion on what they know and encourage them to recall what they have learned so far about nuclear particles. Remind students that, at this stage, they should focus on entering their ideas in their *Active Physics* logs and not be concerned about whether their answers are correct. Ask them to share their ideas and generate a list of questions that they think should be addressed as part of their ongoing inquiry-based investigations. Students should be actively engaged in brainstorming ideas. Accept all responses, recording a few for a later discussion when new physics concepts that explain nuclear energy are introduced.

What Do You Think?

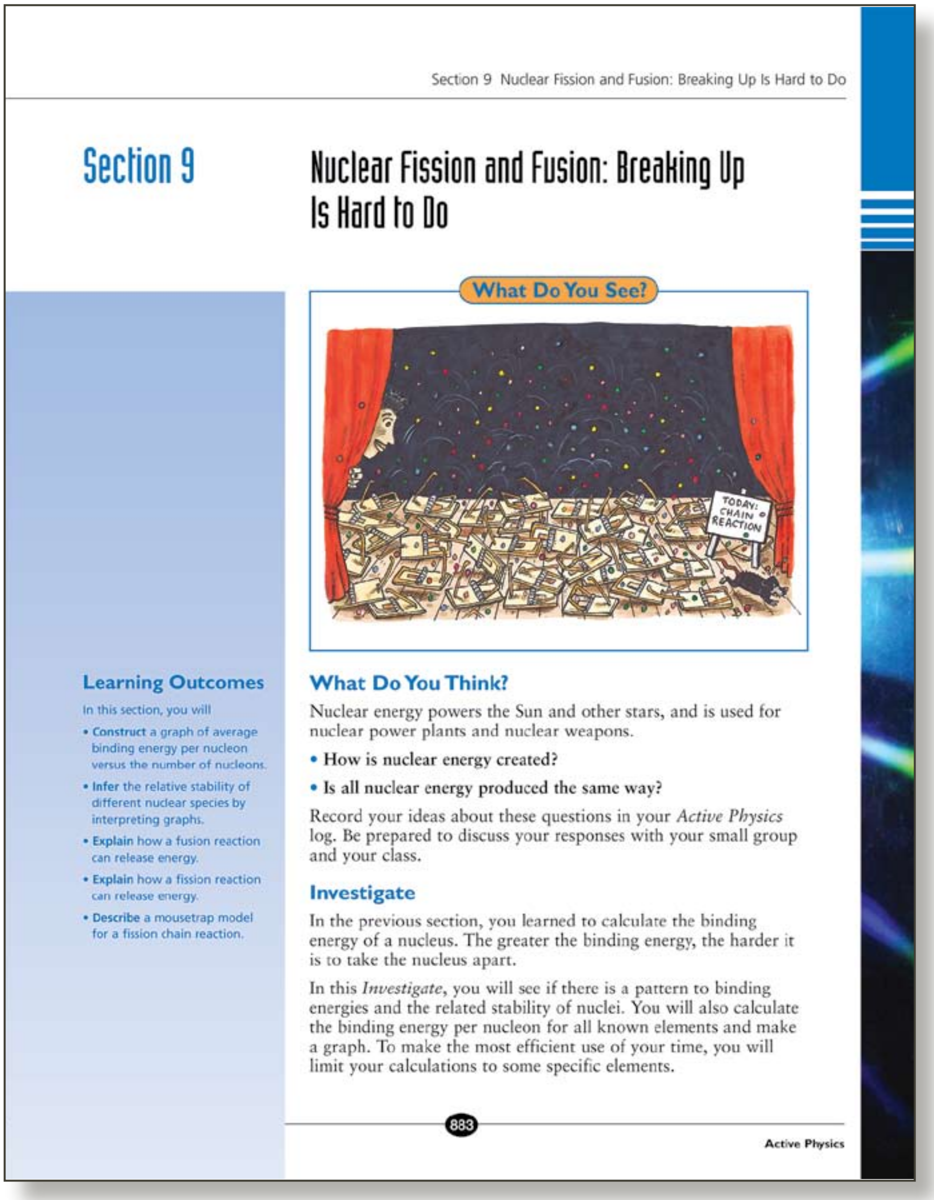
A Physicist's Response

Nuclear energy is created when small nuclei fuse to make larger nuclei (fusion) and when very large nuclei break apart to make smaller nuclei (fission). The energy in nuclear power plants is produced by fission. The energy in the Sun is produced by nuclear fusion. Nuclear weapons are produced by both fission and fusion.

Students' Prior Conceptions

This section explains how atoms with a large nucleus undergo fission when they absorb a neutron. Students learn how a chain reaction is used to produce nuclear power and nuclear bombs. The concept of energy being released during nuclear fusion may be confusing to them, since nuclear fission also releases energy. Point out that during nuclear fusion reactions, two lighter nuclei fuse together to produce a heavier nucleus with a greater average binding energy per nucleon. By constructing the binding energy curve and ensuring that students can explain how the average binding energy per nucleon changes for the different elements affords them the opportunity to best explain both fission and fusion. Other prior conceptions students generally have are as follows:

1. **Nuclear explosions are caused by radioactive decay.** Though radioactive decay is used to initiate the process of fission, a more important factor is the concentration of uranium atoms in a small volume. A critical mass of uranium is required in a reactor or in a bomb before a chain reaction from neutrons colliding with nuclei takes over and releases significant amounts of energy. The radioactive decay of isolated uranium atoms, which generates neutrons, does not lead to a chain reaction that splits the nuclei and releases energy. Therefore, the process of radioactive decay alone, without critical mass being reached, does not set off a nuclear explosion. If it did, radioactive elements in the Earth should be exploding all the time.



Section 9

Nuclear Fission and Fusion: Breaking Up Is Hard to Do

What Do You See?

Learning Outcomes

In this section, you will

- **Construct** a graph of average binding energy per nucleon versus the number of nucleons.
- **Infer** the relative stability of different nuclear species by interpreting graphs.
- **Explain** how a fusion reaction can release energy.
- **Explain** how a fission reaction can release energy.
- **Describe** a mousetrap model for a fission chain reaction.

What Do You Think?

Nuclear energy powers the Sun and other stars, and is used for nuclear power plants and nuclear weapons.

- **How is nuclear energy created?**
- **Is all nuclear energy produced the same way?**

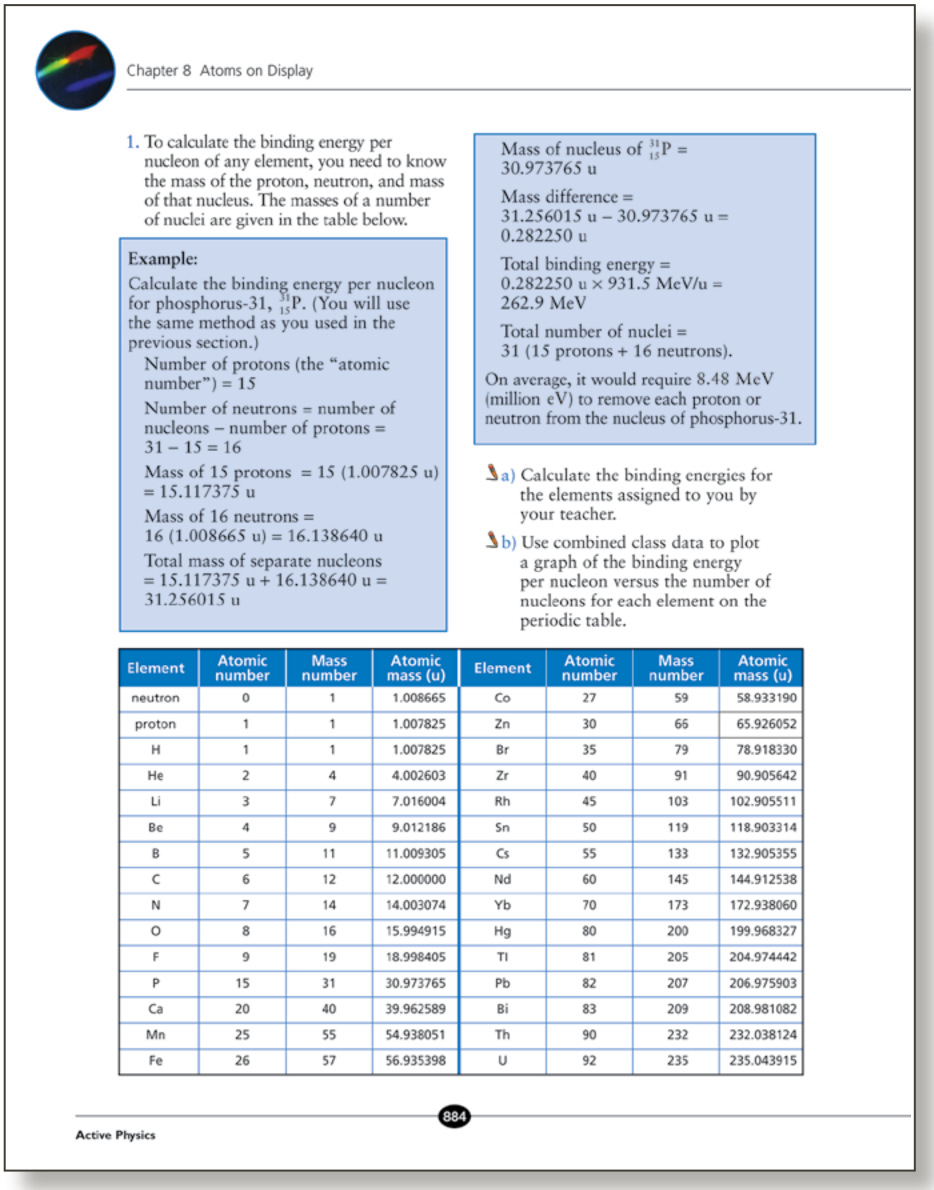
Record your ideas about these questions in your *Active Physics* log. Be prepared to discuss your responses with your small group and your class.

Investigate

In the previous section, you learned to calculate the binding energy of a nucleus. The greater the binding energy, the harder it is to take the nucleus apart.

In this *Investigate*, you will see if there is a pattern to binding energies and the related stability of nuclei. You will also calculate the binding energy per nucleon for all known elements and make a graph. To make the most efficient use of your time, you will limit your calculations to some specific elements.

2. **The Sun provides energy from chemical reactions like burning coal.** Calculations of the amount of material that would have to be burned by the Sun are effective, but difficult. Ask the students where the oxygen needed for the burning comes from in the vacuum of space. Point out that the Sun has been "burning" for about 5 billion years. Consider the amount of coal that would be needed!



Chapter 8 Atoms on Display

1. To calculate the binding energy per nucleon of any element, you need to know the mass of the proton, neutron, and mass of that nucleus. The masses of a number of nuclei are given in the table below.

Example:

Calculate the binding energy per nucleon for phosphorus-31, ${}^{31}_{15}P$. (You will use the same method as you used in the previous section.)

Number of protons (the "atomic number") = 15

Number of neutrons = number of nucleons – number of protons = 31 – 15 = 16

Mass of 15 protons = 15 (1.007825 u) = 15.117375 u

Mass of 16 neutrons = 16 (1.008665 u) = 16.138640 u

Total mass of separate nucleons = 15.117375 u + 16.138640 u = 31.256015 u

Mass of nucleus of ${}^{31}_{15}P$ = 30.973765 u

Mass difference = 31.256015 u – 30.973765 u = 0.282250 u

Total binding energy = 0.282250 u × 931.5 MeV/u = 262.9 MeV

Total number of nuclei = 31 (15 protons + 16 neutrons).

On average, it would require 8.48 MeV (million eV) to remove each proton or neutron from the nucleus of phosphorus-31.

a) Calculate the binding energies for the elements assigned to you by your teacher.

b) Use combined class data to plot a graph of the binding energy per nucleon versus the number of nucleons for each element on the periodic table.

Element	Atomic number	Mass number	Atomic mass (u)	Element	Atomic number	Mass number	Atomic mass (u)
neutron	0	1	1.008665	Co	27	59	58.933190
proton	1	1	1.007825	Zn	30	66	65.926052
H	1	1	1.007825	Br	35	79	78.918330
He	2	4	4.002603	Zr	40	91	90.905642
Li	3	7	7.016004	Rh	45	103	102.905511
Be	4	9	9.012186	Sn	50	119	118.903314
B	5	11	11.009305	Cs	55	133	132.905355
C	6	12	12.000000	Nd	60	145	144.912538
N	7	14	14.003074	Yb	70	173	172.938060
O	8	16	15.994915	Hg	80	200	199.968327
F	9	19	18.998405	Tl	81	205	204.974442
P	15	31	30.973765	Pb	82	207	206.975903
Ca	20	40	39.962589	Bi	83	209	208.981082
Mn	25	55	54.938051	Th	90	232	232.038124
Fe	26	57	56.935398	U	92	235	235.043915

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Investigate

8-9a **Blackline Master**

1.a)

Element	Mass of protons	Mass of neutrons	Total mass	Defect energy	Total binding energy	Binding energy per nucleon
H	1.007825	0.000000	1.007825	0	0	0
He	2.01565	2.01733	4.03298	0.030377	28.29618	7.074044
Li	3.023475	4.03466	7.058135	0.042131	39.24503	5.606432
Be	4.0313	5.043325	9.074625	0.062439	58.16193	6.462436
B	5.039125	6.05199	11.09112	0.081810	76.20602	6.92782
C	6.04695	6.05199	12.09894	0.098940	92.16261	7.680217
N	7.054775	7.060655	14.11543	0.112356	104.6596	7.475687
O	8.0626	8.06932	16.13192	0.137005	127.6202	7.97626
F	9.070425	10.08665	19.15708	0.158670	147.8011	7.779006
P	15.11738	16.13864	31.25602	0.282250	262.9159	8.481157
Ca	20.1565	20.1733	40.3298	0.367211	342.057	8.551426
Mn	25.19563	30.25995	55.45558	0.517524	482.0736	8.764975
Fe	26.20345	31.26862	57.47207	0.536667	499.9053	8.770269
Co	27.21128	32.27728	59.48856	0.555365	517.3225	8.768178
Zn	30.23475	36.31194	66.54669	0.620638	578.1243	8.759459
Br	35.27388	44.38126	79.65514	0.736805	686.3339	8.68777
Zr	40.313	51.44192	91.75492	0.849273	791.0978	8.693382
Rh	45.35213	58.50257	103.8547	0.949184	884.1649	8.584125
Sn	50.39125	69.59789	119.9891	1.085821	1011.442	8.499515
Cs	55.43038	78.67587	134.1062	1.200890	1118.629	8.410745
Nd	60.4695	85.73653	146.206	1.293487	1204.883	8.309539
Yb	70.54775	103.8925	174.4402	1.502185	1399.285	8.088354
Hg	80.626	121.0398	201.6658	1.697473	1581.196	7.90598
Tl	81.63383	125.0745	206.7083	1.733843	1615.075	7.878413
Pb	82.64165	126.0831	208.7248	1.748872	1629.074	7.869924
Bi	83.64948	127.0918	210.7413	1.760183	1639.61	7.845026
Th	90.70425	143.2304	233.9347	1.896556	1766.642	7.614836
U	92.7199	144.2391	236.959	1.91508	1783.897	7.591051

1.b)

The graph is shown in text in *Step 2*.

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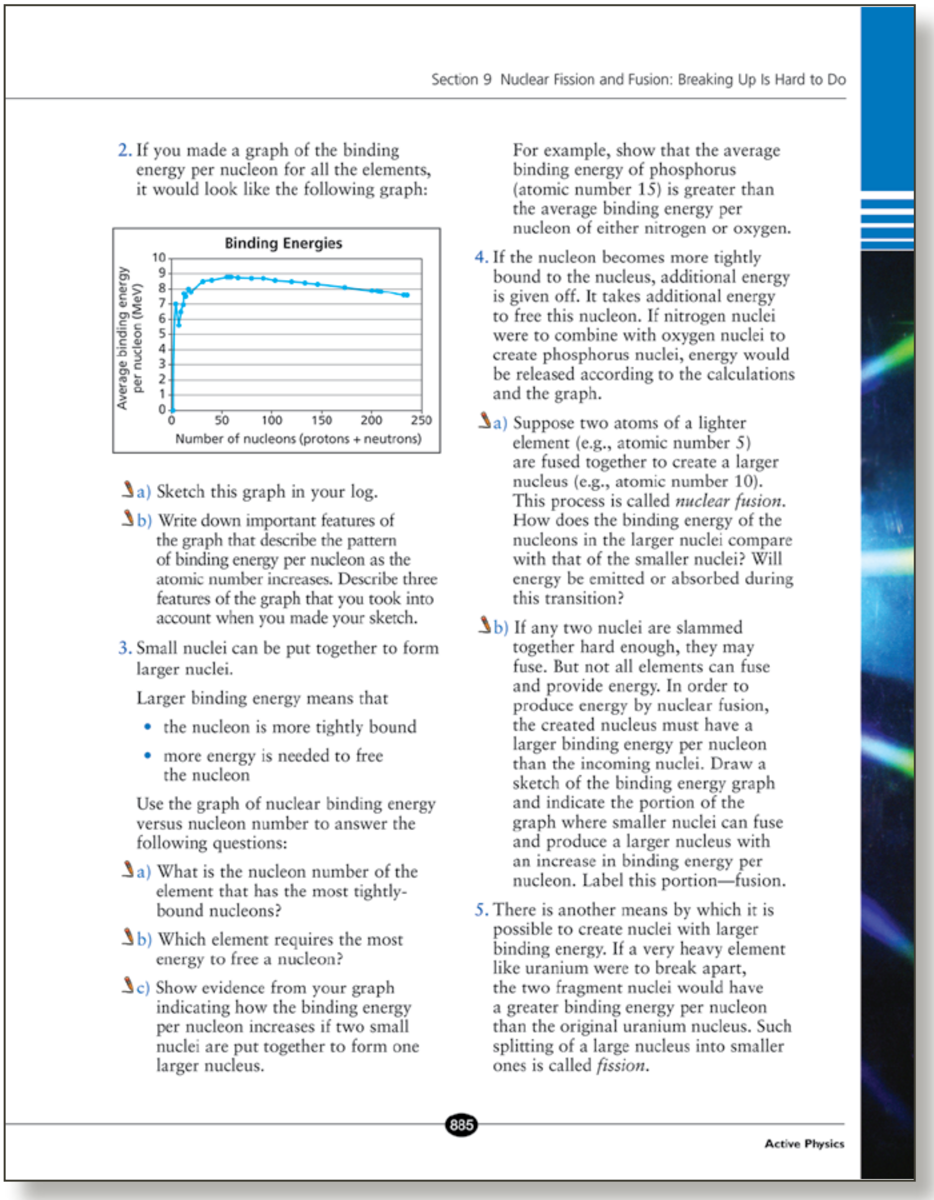

Section 9 Nuclear Fission and Fusion: Breaking Up Is Hard to Do

2. If you made a graph of the binding energy per nucleon for all the elements, it would look like the following graph:

a) Sketch this graph in your log.

b) Write down important features of the graph that describe the pattern of binding energy per nucleon as the atomic number increases. Describe three features of the graph that you took into account when you made your sketch.

3. Small nuclei can be put together to form larger nuclei.

Larger binding energy means that

- the nucleon is more tightly bound
- more energy is needed to free the nucleon

Use the graph of nuclear binding energy versus nucleon number to answer the following questions:

a) What is the nucleon number of the element that has the most tightly-bound nucleons?

b) Which element requires the most energy to free a nucleon?

c) Show evidence from your graph indicating how the binding energy per nucleon increases if two small nuclei are put together to form one larger nucleus.

For example, show that the average binding energy of phosphorus (atomic number 15) is greater than the average binding energy per nucleon of either nitrogen or oxygen.

4. If the nucleon becomes more tightly bound to the nucleus, additional energy is given off. It takes additional energy to free this nucleon. If nitrogen nuclei were to combine with oxygen nuclei to create phosphorus nuclei, energy would be released according to the calculations and the graph.

a) Suppose two atoms of a lighter element (e.g., atomic number 5) are fused together to create a larger nucleus (e.g., atomic number 10). This process is called *nuclear fusion*. How does the binding energy of the nucleons in the larger nuclei compare with that of the smaller nuclei? Will energy be emitted or absorbed during this transition?

b) If any two nuclei are slammed together hard enough, they may fuse. But not all elements can fuse and provide energy. In order to produce energy by nuclear fusion, the created nucleus must have a larger binding energy per nucleon than the incoming nuclei. Draw a sketch of the binding energy graph and indicate the portion of the graph where smaller nuclei can fuse and produce a larger nucleus with an increase in binding energy per nucleon. Label this portion—fusion.

5. There is another means by which it is possible to create nuclei with larger binding energy. If a very heavy element like uranium were to break apart, the two fragment nuclei would have a greater binding energy per nucleon than the original uranium nucleus. Such splitting of a large nucleus into smaller ones is called *fission*.

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2.a)

Students sketch the graph in their notebooks.

2.b)

Features of the graph that describe the pattern of binding energy per nucleon as the atomic number increases are

- a sharp increase in average binding energy for small numbers of nucleons
- a gradual decrease in average binding energy for large numbers of nucleons
- a maximum value of binding energy corresponding to Fe (iron) with 57 nucleons.

3.a)

Fe (57 nucleons) has the largest average binding energy per nucleon.

3.b)

Fe requires the most energy to free each nucleon.

3.c)

When two small nuclei with average binding energies of 7 MeV per nucleon combine, they form a larger nucleus. This nucleus, according to the graph, may have an average binding energy of 8 MeV per nucleon. This would mean that each nucleon has a larger binding energy and has released energy in forming the larger nucleus.

4.a)

The larger nucleus has more average binding energy for each nucleon. Some energy is emitted when these nuclei fuse.

4.b)

The binding energy graph should have a vertical line drawn at Fe (number of nucleons = 57) and "fusion" should be noted for the portion to the left of this line.

5.a)

7.59 MeV

5.b)

8.35 MeV

5.c)

8.7 MeV

6.a)

The binding-energy graph now has a vertical line drawn at Fe (number of nucleons = 57) and "fission" should be noted for the portion to the right of this line.

7.a)

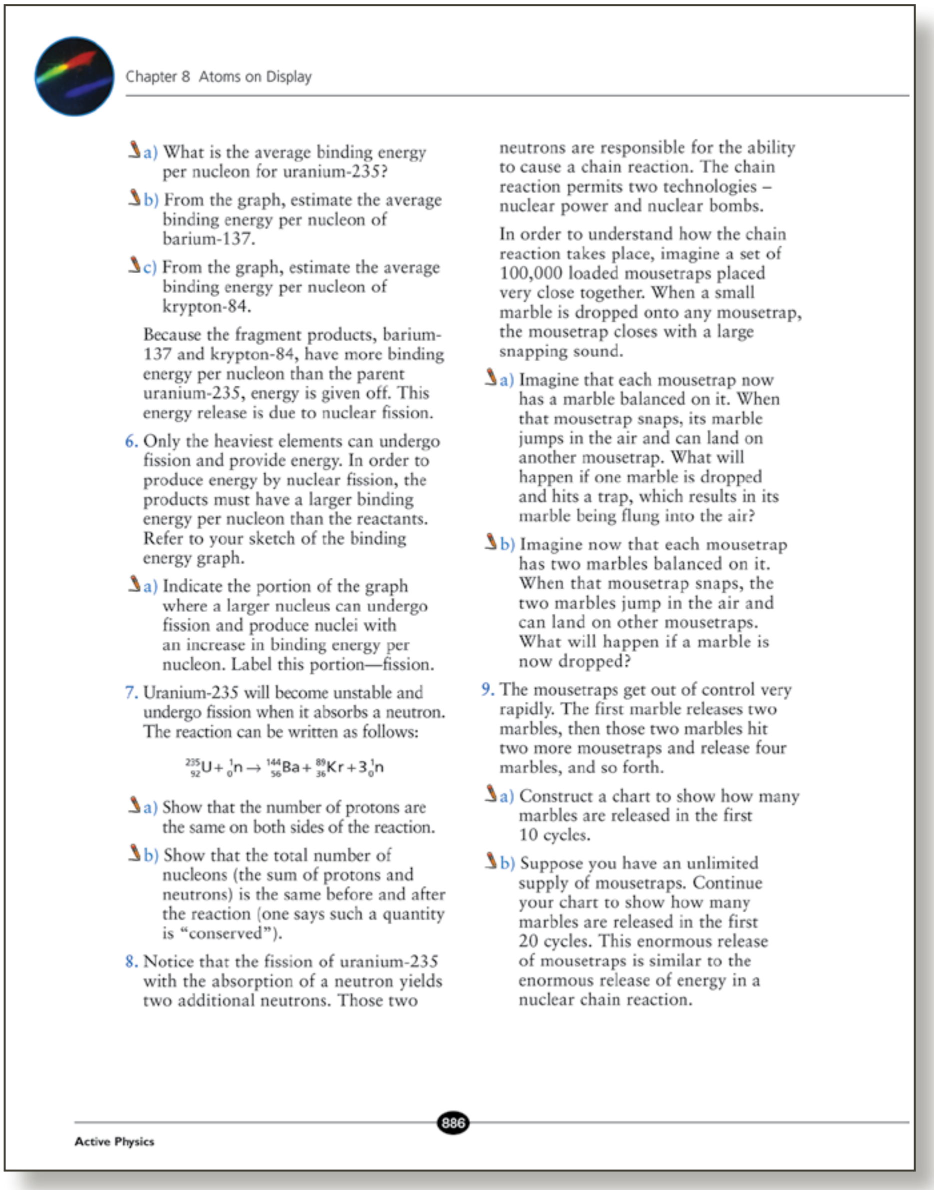
Number of protons are the bottom numbers: $92 + 0 = 56 + 36 + 0$

7.b)

The number of nucleons are the top numbers: $235 + 1 = 144 + 89 + 3$ (The 3 comes from the fact that there are 3 neutrons emitted.)

8.a)

The mousetrap that is hit will close, which will release a marble into the air. If this marble strikes another mousetrap, that mousetrap will release its marble into the air, which may strike another mousetrap causing it to close, and so on. This process will continue until the last marble launched misses a mousetrap or hits one that has already released its marble, causing the reaction to stop. (If you have ever done this with an array of real mousetraps, you know that when the trap closes, it jumps, which sets off nearby mousetraps even if there are no more marbles. In the questions asked here, we are to assume that when a mousetrap closes it does not jump, and will therefore not set off another mousetrap unless it had a marble on its spring.)



Chapter 8 Atoms on Display

a) What is the average binding energy per nucleon for uranium-235?

b) From the graph, estimate the average binding energy per nucleon of barium-137.

c) From the graph, estimate the average binding energy per nucleon of krypton-84.

Because the fragment products, barium-137 and krypton-84, have more binding energy per nucleon than the parent uranium-235, energy is given off. This energy release is due to nuclear fission.

6. Only the heaviest elements can undergo fission and provide energy. In order to produce energy by nuclear fission, the products must have a larger binding energy per nucleon than the reactants. Refer to your sketch of the binding energy graph.

a) Indicate the portion of the graph where a larger nucleus can undergo fission and produce nuclei with an increase in binding energy per nucleon. Label this portion—fission.

7. Uranium-235 will become unstable and undergo fission when it absorbs a neutron. The reaction can be written as follows:

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{144}_{56}\mathrm{Ba} + ^{89}_{36}\mathrm{Kr} + 3^{1}_{0}\mathrm{n}$$

a) Show that the number of protons are the same on both sides of the reaction.

b) Show that the total number of nucleons (the sum of protons and neutrons) is the same before and after the reaction (one says such a quantity is "conserved").

8. Notice that the fission of uranium-235 with the absorption of a neutron yields two additional neutrons. Those two neutrons are responsible for the ability to cause a chain reaction. The chain reaction permits two technologies – nuclear power and nuclear bombs.

In order to understand how the chain reaction takes place, imagine a set of 100,000 loaded mousetraps placed very close together. When a small marble is dropped onto any mousetrap, the mousetrap closes with a large snapping sound.

a) Imagine that each mousetrap now has a marble balanced on it. When that mousetrap snaps, its marble jumps in the air and can land on another mousetrap. What will happen if one marble is dropped and hits a trap, which results in its marble being flung into the air?

b) Imagine now that each mousetrap has two marbles balanced on it. When that mousetrap snaps, the two marbles jump in the air and can land on other mousetraps. What will happen if a marble is now dropped?

9. The mousetraps get out of control very rapidly. The first marble releases two marbles, then those two marbles hit two more mousetraps and release four marbles, and so forth.

a) Construct a chart to show how many marbles are released in the first 10 cycles.

b) Suppose you have an unlimited supply of mousetraps. Continue your chart to show how many marbles are released in the first 20 cycles. This enormous release of mousetraps is similar to the enormous release of energy in a nuclear chain reaction.

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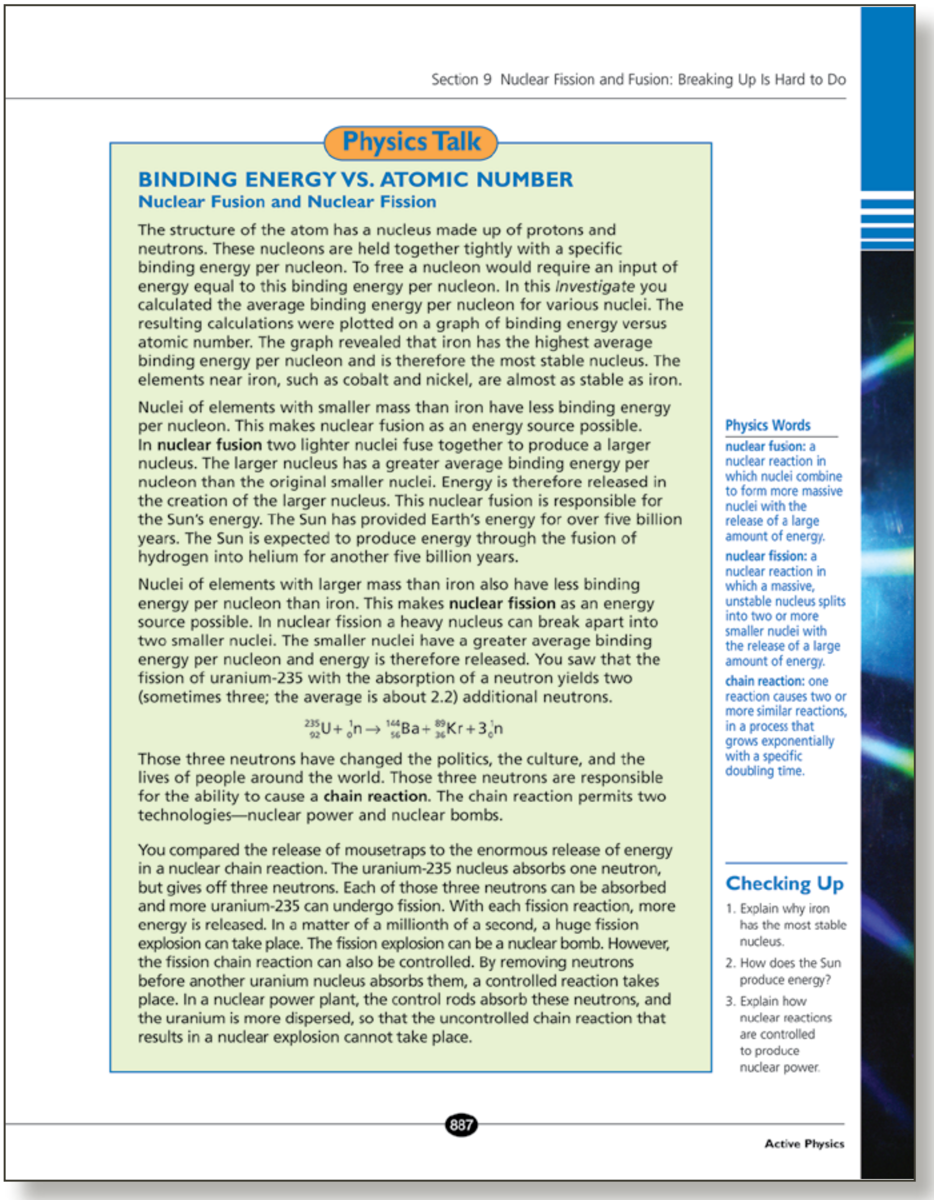
8.b)

The first mousetrap releases two marbles, which can then fall on two other mousetraps, causing them to release their marbles, so now four marbles are in the air. These four marbles will land on four other mousetraps, causing the release of eight marbles, and so on. Assuming no marbles hit traps that have been previously struck, the process continues exponentially until all the mousetraps have been hit. This occurs after 17 iterations of this process $\left(2^{17} = 131{,}072\right)$.



Section 9 Nuclear Fission and Fusion: Breaking Up Is Hard to Do

Physics Talk

BINDING ENERGY VS. ATOMIC NUMBER

Nuclear Fusion and Nuclear Fission

The structure of the atom has a nucleus made up of protons and neutrons. These nucleons are held together tightly with a specific binding energy per nucleon. To free a nucleon would require an input of energy equal to this binding energy per nucleon. In this *Investigate* you calculated the average binding energy per nucleon for various nuclei. The resulting calculations were plotted on a graph of binding energy versus atomic number. The graph revealed that iron has the highest average binding energy per nucleon and is therefore the most stable nucleus. The elements near iron, such as cobalt and nickel, are almost as stable as iron.

Nuclei of elements with smaller mass than iron have less binding energy per nucleon. This makes nuclear fusion as an energy source possible. In **nuclear fusion** two lighter nuclei fuse together to produce a larger nucleus. The larger nucleus has a greater average binding energy per nucleon than the original smaller nuclei. Energy is therefore released in the creation of the larger nucleus. This nuclear fusion is responsible for the Sun's energy. The Sun has provided Earth's energy for over five billion years. The Sun is expected to produce energy through the fusion of hydrogen into helium for another five billion years.

Nuclei of elements with larger mass than iron also have less binding energy per nucleon than iron. This makes **nuclear fission** as an energy source possible. In nuclear fission a heavy nucleus can break apart into two smaller nuclei. The smaller nuclei have a greater average binding energy per nucleon and energy is therefore released. You saw that the fission of uranium-235 with the absorption of a neutron yields two (sometimes three; the average is about 2.2) additional neutrons.

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{144}_{56}\mathrm{Ba} + ^{89}_{36}\mathrm{Kr} + 3\,^{1}_{0}\mathrm{n}$$

Those three neutrons have changed the politics, the culture, and the lives of people around the world. Those three neutrons are responsible for the ability to cause a **chain reaction**. The chain reaction permits two technologies—nuclear power and nuclear bombs.

You compared the release of mousetraps to the enormous release of energy in a nuclear chain reaction. The uranium-235 nucleus absorbs one neutron, but gives off three neutrons. Each of those three neutrons can be absorbed and more uranium-235 can undergo fission. With each fission reaction, more energy is released. In a matter of a millionth of a second, a huge fission explosion can take place. The fission explosion can be a nuclear bomb. However, the fission chain reaction can also be controlled. By removing neutrons before another uranium nucleus absorbs them, a controlled reaction takes place. In a nuclear power plant, the control rods absorb these neutrons, and the uranium is more dispersed, so that the uncontrolled chain reaction that results in a nuclear explosion cannot take place.

Physics Words

nuclear fusion: a nuclear reaction in which nuclei combine to form more massive nuclei with the release of a large amount of energy.

nuclear fission: a nuclear reaction in which a massive, unstable nucleus splits into two or more smaller nuclei with the release of a large amount of energy.

chain reaction: one reaction causes two or more similar reactions, in a process that grows exponentially with a specific doubling time.

Checking Up

1. Explain why iron has the most stable nucleus.
2. How does the Sun produce energy?
3. Explain how nuclear reactions are controlled to produce nuclear power.

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Active Physics

9.a)

Cycle	Marbles released
1	2
2	4
3	8
4	16
5	32
6	64
7	128
8	256
9	512
10	1,024

9.b)

Cycle	Marbles released
11	2,048
12	4,096
13	8,192
14	16,384
15	32,768
16	65,536
17	131,072
18	262,144
19	524,288
20	1,048,586

Physics Talk

Students read how the average binding energy per nucleon is related to atomic number and to the stability of a nucleus. Experiments from the *Investigate* are recalled to explain the processes of nuclear fusion and fission. Iron and other elements near iron in the periodic table, when plotted on a graph of binding energy versus atomic number, reveal that these elements are the most stable. Students discover that elements that have smaller masses than iron have less binding energy per nucleon, which makes nuclear fusion possible. Nuclear fusion powers the Sun as hydrogen is converted into helium. Elements with atomic number and masses higher than iron also have less binding energy per nucleon, which makes nuclear fission possible.

Ask students why nuclear fission takes place and with which elements nuclear fission is possible. Students should be able to give a brief description of nuclear fission using the atom of an element as an example. Consider drawing a diagram on the board to illustrate this process. Initiate a discussion on nuclear fission as a result of a chain reaction, and have students describe in their logs why nuclear power is a result of a chain reaction. Have them distinguish between the difference in technologies used for nuclear bombs and nuclear power.

Checking Up

1.

Iron has the most stable nucleus because it has the greatest binding energy per nucleon of any element.

2.

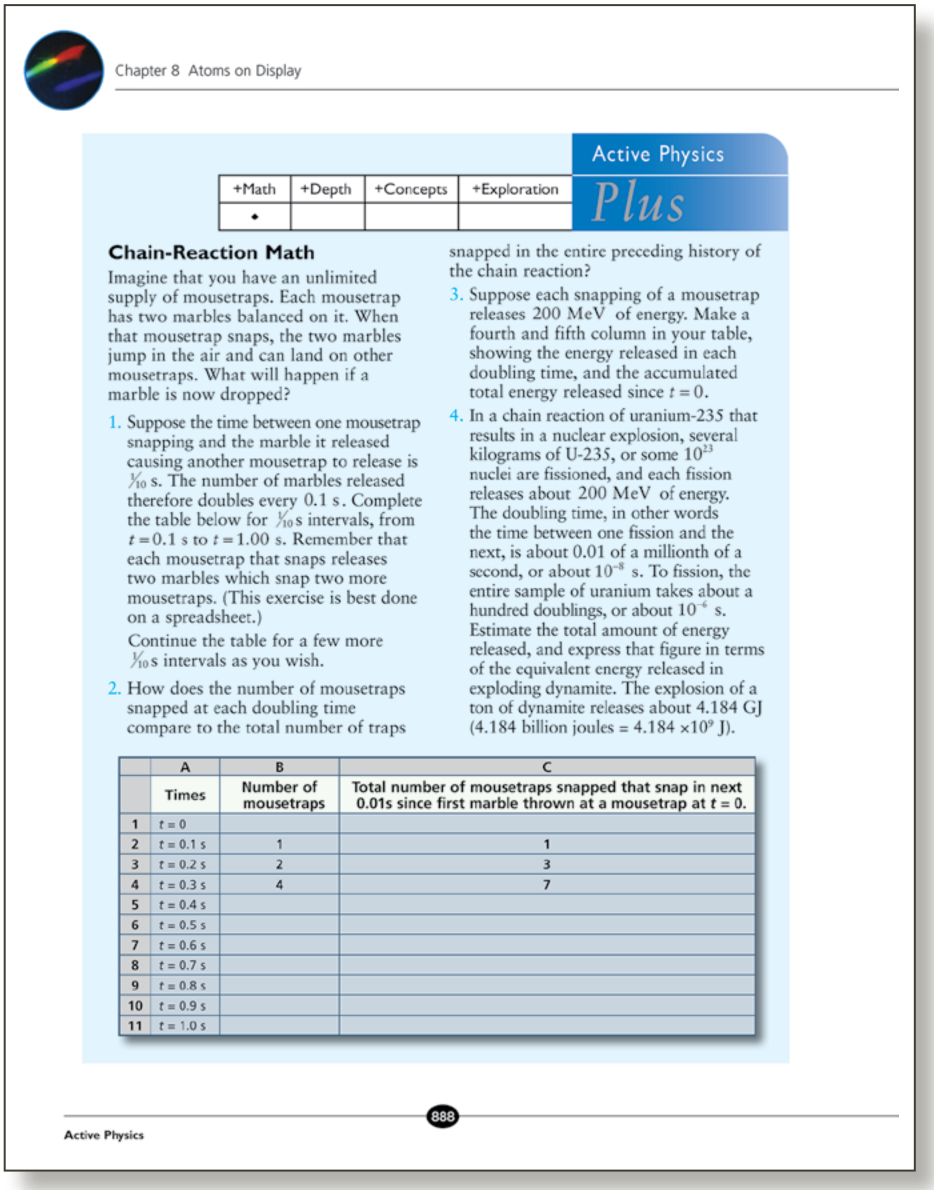
The Sun produces energy by the fusion of hydrogen into helium. Four hydrogen atoms are forced together under very high temperatures to produce a helium nucleus and two positive electrons. Helium plus the positive electrons has a lower mass than the four hydrogen atoms, with the excess mass being converted into energy.

3.

Nuclear reactors control the fission of uranium by using control rods to absorb the extra neutrons emitted by uranium during the fission process. When exactly balanced, one uranium fission will lead to another uranium fission, so that energy is produced at a constant rate.

Active Physics Plus

Students explore the exponential relationship that simulates what occurs in a nuclear explosion. They begin by discovering what occurs in a system where the number of events doubles after each action (in this case a group of mousetraps that snap, inducing two additional snaps for each mousetrap). They note that the number of "snaps" occurring every 0.1 seconds is equal to approximately one-half the total snaps that have occurred since the start of the process. This process is then related to the energy release process that occurs in an uncontrolled fission reaction such as a nuclear explosion.



Chapter 8 Atoms on Display

Active Physics Plus

+Math	+Depth	+Concepts	+Exploration
•			

Chain-Reaction Math

Imagine that you have an unlimited supply of mousetraps. Each mousetrap has two marbles balanced on it. When that mousetrap snaps, the two marbles jump in the air and can land on other mousetraps. What will happen if a marble is now dropped?

1. Suppose the time between one mousetrap snapping and the marble it released causing another mousetrap to release is $\frac{1}{10}$ s. The number of marbles released therefore doubles every 0.1 s. Complete the table below for $\frac{1}{10}$ s intervals, from $t = 0.1$ s to $t = 1.00$ s. Remember that each mousetrap that snaps releases two marbles which snap two more mousetraps. (This exercise is best done on a spreadsheet.)

   Continue the table for a few more $\frac{1}{10}$ s intervals as you wish.
2. How does the number of mousetraps snapped at each doubling time compare to the total number of traps snapped in the entire preceding history of the chain reaction?
3. Suppose each snapping of a mousetrap releases 200 MeV of energy. Make a fourth and fifth column in your table, showing the energy released in each doubling time, and the accumulated total energy released since $t = 0$.
4. In a chain reaction of uranium-235 that results in a nuclear explosion, several kilograms of U-235, or some 10^{23} nuclei are fissioned, and each fission releases about 200 MeV of energy. The doubling time, in other words the time between one fission and the next, is about 0.01 of a millionth of a second, or about 10^{-8} s. To fission, the entire sample of uranium takes about a hundred doublings, or about 10^{-6} s. Estimate the total amount of energy released, and express that figure in terms of the equivalent energy released in exploding dynamite. The explosion of a ton of dynamite releases about 4.184 GJ (4.184 billion joules = 4.184×10^9 J).

	A	B	C
	Times	Number of mousetraps	Total number of mousetraps snapped that snap in next 0.01s since first marble thrown at a mousetrap at $t = 0$.
1	$t = 0$		
2	$t = 0.1$ s	1	1
3	$t = 0.2$ s	2	3
4	$t = 0.3$ s	4	7
5	$t = 0.4$ s		
6	$t = 0.5$ s		
7	$t = 0.6$ s		
8	$t = 0.7$ s		
9	$t = 0.8$ s		
10	$t = 0.9$ s		
11	$t = 1.0$ s		

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1.

	A	B	C
	Times	Number of mousetraps	Total number
1	$t = 0$		
2	$t = 0.1$ s	1	1
3	$t = 0.2$ s	2	3
4	$t = 0.3$ s	4	7
5	$t = 0.4$ s	8	15
6	$t = 0.5$ s	16	31
7	$t = 0.6$ s	32	63
8	$t = 0.7$ s	64	127
9	$t = 0.8$ s	128	255
10	$t = 0.9$ s	256	511
11	$t = 1.0$ s	512	1023

2.

The total number of mousetraps snapping each second is one half the total number of mousetraps plus one snapped in all the previous snaps combined.

3.

	A	B	C	D	E
	Times	**Number of Mousetraps**	**Total number**	**Energy released (MeV)**	**Total energy released**
1	$t = 0$				
2	$t = 0.1$ s	1	1	200	200
3	$t = 0.2$ s	2	3	400	600
4	$t = 0.3$ s	4	7	800	1400
5	$t = 0.4$ s	8	15	1600	3000
6	$t = 0.5$ s	16	31	3200	6200
7	$t = 0.6$ s	32	63	6400	12,600
8	$t = 0.7$ s	64	127	12,800	25,400
9	$t = 0.8$ s	128	255	25,600	51,000
10	$t = 0.9$ s	256	511	51,200	102,200
11	$t = 1.0$ s	512	1023	102,400	204,600

4.

Assume 10^{23} nuclei of Uranium is fission at 200 MeV/fission. This gives a total energy of 2×10^{25} MeV $= 2\times10^{31}$ eV. Converting eV to joules gives

$$\left(2\times10^{31}\text{ eV}\right)\left(1.6\times10^{-19}\text{ J/eV}\right) =$$

3.2×10^{12} J.

If one ton (1 T) of dynamite releases 4.184×10^{9} J when it explodes, then the energy released by the uranium during the fission process is equal to

$$\left(3.2\times10^{12}\text{ J}\right)/\left(4.184\times10^{9}\text{ J/T}\right) =$$

765 T of dynamite.

NOTES

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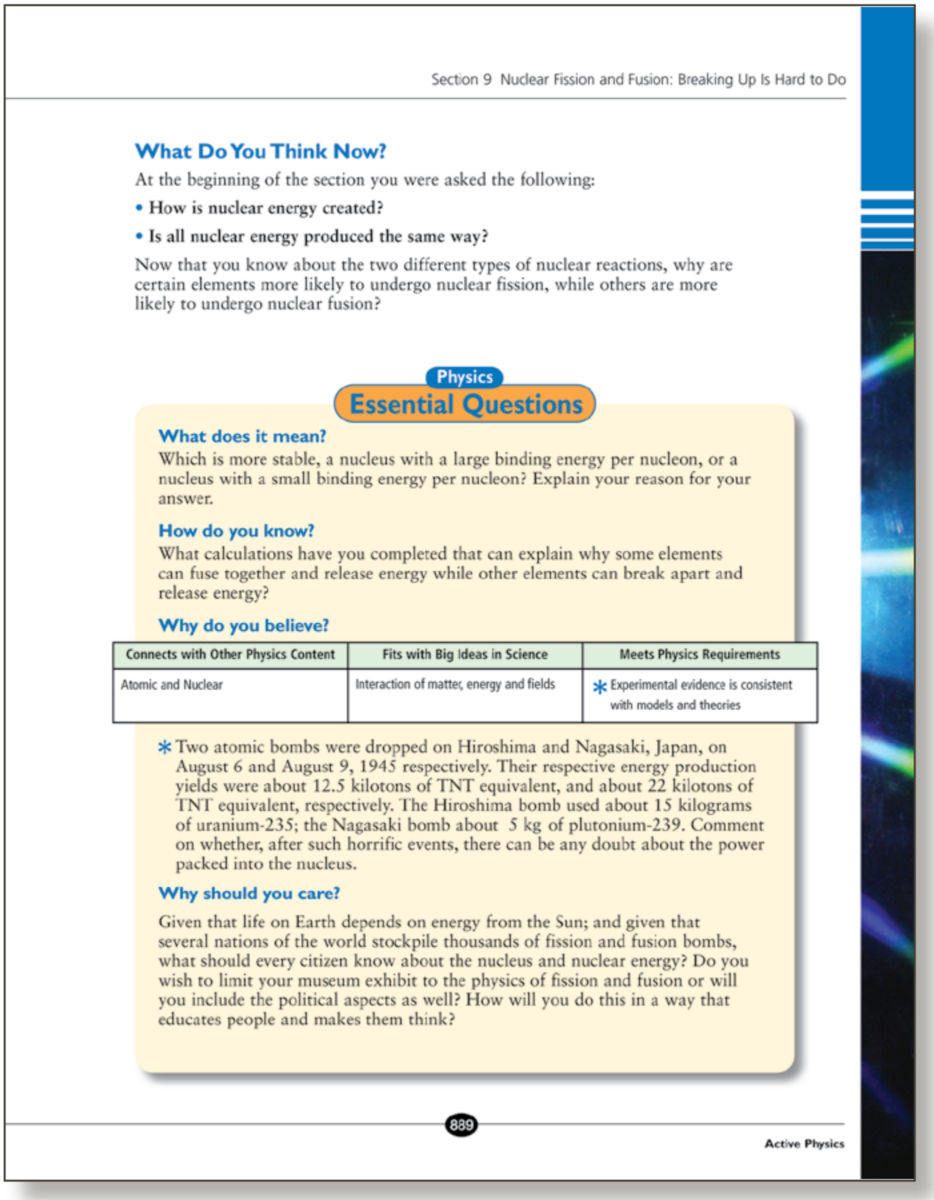

Section 9 Nuclear Fission and Fusion: Breaking Up Is Hard to Do

What Do You Think Now?

At the beginning of the section you were asked the following:

- How is nuclear energy created?
- Is all nuclear energy produced the same way?

Now that you know about the two different types of nuclear reactions, why are certain elements more likely to undergo nuclear fission, while others are more likely to undergo nuclear fusion?

Physics

Essential Questions

What does it mean?

Which is more stable, a nucleus with a large binding energy per nucleon, or a nucleus with a small binding energy per nucleon? Explain your reason for your answer.

How do you know?

What calculations have you completed that can explain why some elements can fuse together and release energy while other elements can break apart and release energy?

Why do you believe?

Connects with Other Physics Content	Fits with Big Ideas in Science	Meets Physics Requirements
Atomic and Nuclear	Interaction of matter, energy and fields	✱ Experimental evidence is consistent with models and theories

✱ Two atomic bombs were dropped on Hiroshima and Nagasaki, Japan, on August 6 and August 9, 1945 respectively. Their respective energy production yields were about 12.5 kilotons of TNT equivalent, and about 22 kilotons of TNT equivalent, respectively. The Hiroshima bomb used about 15 kilograms of uranium-235; the Nagasaki bomb about 5 kg of plutonium-239. Comment on whether, after such horrific events, there can be any doubt about the power packed into the nucleus.

Why should you care?

Given that life on Earth depends on energy from the Sun; and given that several nations of the world stockpile thousands of fission and fusion bombs, what should every citizen know about the nucleus and nuclear energy? Do you wish to limit your museum exhibit to the physics of fission and fusion or will you include the political aspects as well? How will you do this in a way that educates people and makes them think?

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Active Physics

What Do You Think Now?

Students should be able to describe the difference between nuclear fission and nuclear fusion, including why certain elements are likely to undergo nuclear fission while other elements are likely to undergo fusion. Provide students with *A Physicist's Response* and discuss examples from the *Investigate* and *Physics Talk* to highlight what students should now know about nuclear energy. Point out that you will be evaluating students' answers to see whether they have understood the main concepts presented in this section. Encourage them to review and edit their previous responses, so that they can illustrate how clearly they have understood the concept of nuclear energy.

Physics Essential Questions

What does it mean?

The nucleus with the large binding energy per nucleon is more stable. The binding energy is a measure of the energy required to remove a nucleon from the nucleus. The more energy required, the more stable the nucleus.

How do you know?

The calculations showing the binding energy per nucleon show that fusing lighter nuclei can result in a larger binding energy and breaking heavier nuclei can also result in a larger binding energy.

Why do you believe?

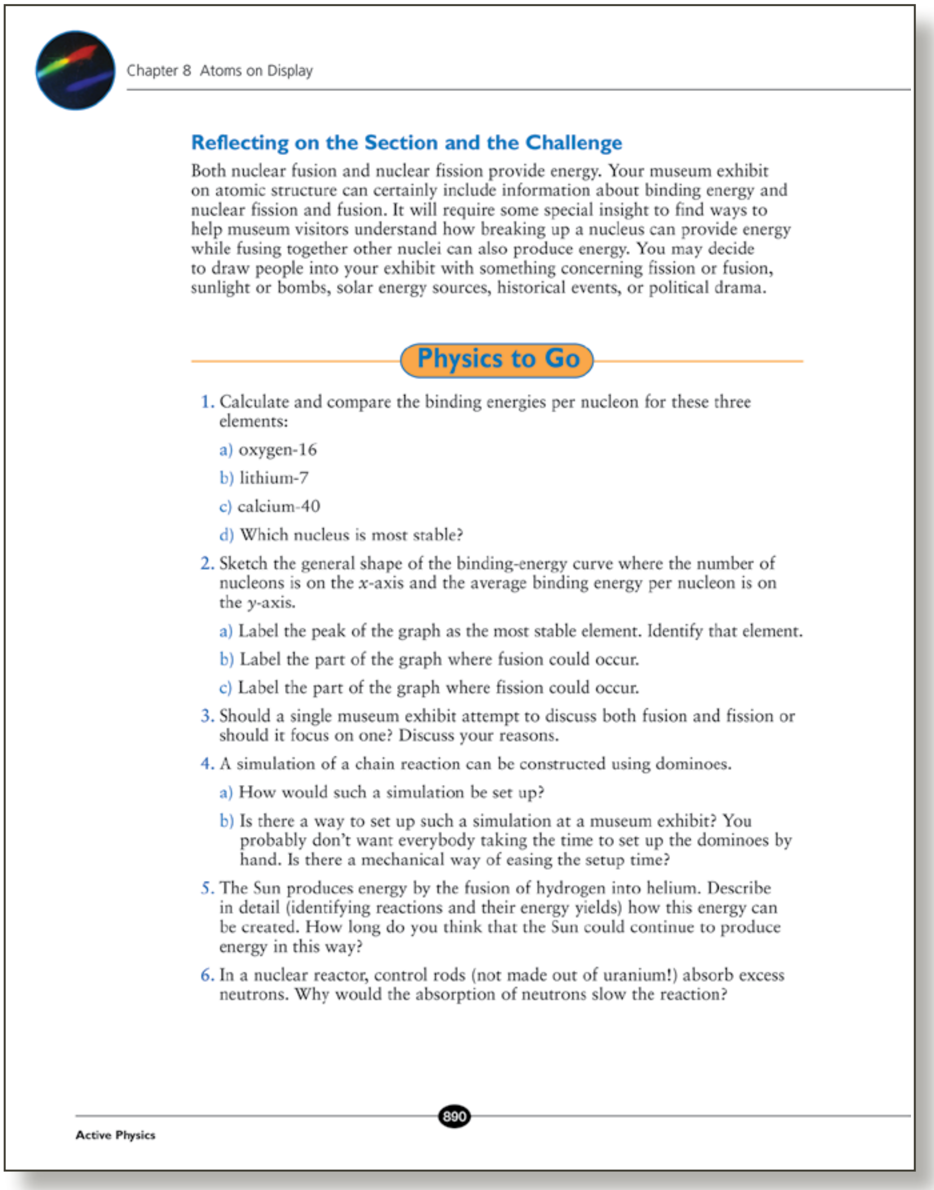
15 kilograms of uranium had the destructive power of approximately 15 kilotons (15,000 tons is approximately 15,000,000 kilograms) of TNT. Each kilogram of uranium has the destructive power of one million kilograms of TNT.

Why should you care?

That the Sun is able to provide all the energy for billions of years through the fusion of nuclei is a fascinating answer to a question that puzzled many people. "How does the Sun produce its energy?" Nuclear power can be beneficial or dangerous. Including this in a museum display requires tact.

Reflecting on the Section and the Challenge

Students can now reflect on what they have read in this section about nuclear energy. Nuclear fission and nuclear fusion are processes that require students to understand the structure of a nucleus and why lighter nuclei are able to fuse while heavier ones are likely to undergo fission. Ask students to think of ways in which they can incorporate the physics of nuclear energy, its advantages and hazards, in their *Chapter Challenge* exhibit. The *What Do You See?* section can be used as a resource to suggest techniques that use creative styles of expression in conveying important science concepts. Consider asking students to briefly describe how their museum display will apply their knowledge of nuclear reactions and engage their audience.



Chapter 8 Atoms on Display

Reflecting on the Section and the Challenge

Both nuclear fusion and nuclear fission provide energy. Your museum exhibit on atomic structure can certainly include information about binding energy and nuclear fission and fusion. It will require some special insight to find ways to help museum visitors understand how breaking up a nucleus can provide energy while fusing together other nuclei can also produce energy. You may decide to draw people into your exhibit with something concerning fission or fusion, sunlight or bombs, solar energy sources, historical events, or political drama.

Physics to Go

1. Calculate and compare the binding energies per nucleon for these three elements:
   a) oxygen-16
   b) lithium-7
   c) calcium-40
   d) Which nucleus is most stable?
2. Sketch the general shape of the binding-energy curve where the number of nucleons is on the *x*-axis and the average binding energy per nucleon is on the *y*-axis.
   a) Label the peak of the graph as the most stable element. Identify that element.
   b) Label the part of the graph where fusion could occur.
   c) Label the part of the graph where fission could occur.
3. Should a single museum exhibit attempt to discuss both fusion and fission or should it focus on one? Discuss your reasons.
4. A simulation of a chain reaction can be constructed using dominoes.
   a) How would such a simulation be set up?
   b) Is there a way to set up such a simulation at a museum exhibit? You probably don't want everybody taking the time to set up the dominoes by hand. Is there a mechanical way of easing the setup time?
5. The Sun produces energy by the fusion of hydrogen into helium. Describe in detail (identifying reactions and their energy yields) how this energy can be created. How long do you think that the Sun could continue to produce energy in this way?
6. In a nuclear reactor, control rods (not made out of uranium!) absorb excess neutrons. Why would the absorption of neutrons slow the reaction?

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Active Physics

Physics to Go

1.a)–c)

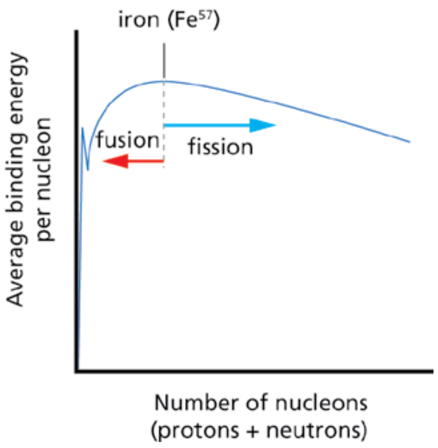
	Number of protons	Number of nucleons	Number of neutrons	Atomic mass (u)
neutron	0	1	1	1.008 665
proton	1	1	0	1.007 825
O-16	8	16	8	15.994 915
Li-7	3	7	4	7.016 004
Ca-40	20	40	20	39.962 589

	Mass of separate neutrons and protons (u)	Mass defect (u)	Binding energy energy (MeV)	Binding energy per nucleon (MeV/nucleon)
O-16	16.13192	0.137005	127.6202	7.97626
Li-7	7.058135	0.042131	39.24503	5.606432
Ca-40	40.3298	0.367211	342.057	8.551426

1.d)

Calcium-40 has the strongest binding energy and is therefore the most stable.

2.a)–c)



3.

Student answers will vary.

4.a)

One falling domino would hit two dominoes. These two dominoes would hit four that would then hit eight, that would then hit sixteen dominoes, etc.

4.b)

Answers will vary. A tool can probably be set up where the dominoes are hinged at the bottom and they can all be set standing with a rotation of the base.

5.

A general expression for fusion in the Sun is $4\,{}^{1}_{1}\text{H} \rightarrow {}^{4}_{2}\text{He} + 2\,{}^{0}_{+1}\text{e}$. When hydrogen fuses together to form helium, approximately 28 MeV are released per fusion. This energy is the source of the radiation in the form of light and heat that emanates from the Sun.

Scientists expect the energy of fusion to be sufficient to power the Sun for at least the next five billion years.

6.

If the extra neutrons are absorbed, fewer neutrons can be absorbed by the uranium and less uranium will undergo fission since a captured neutron is required to start the fission reaction.

NOTES

7.

Answers will vary.

8.

Research is being performed in several national labs to develop a device for controlled nuclear fusion. The two main approaches are the Tokamak, which uses magnetic confinement to force the nuclei together, and Laser confinement, which uses high energy laser pulses to smash them together. More information can be discovered in an Internet search.

9.

The major advantage to fission as an energy source is that, when properly used, it produces no atmospheric pollution. In addition, fission is a source of energy that could power the world's economies for many years to come, allowing conservation of the non-renewable resources such as oil and natural gas. One of the main disadvantages to fission as a power source is that the products formed by the fission of uranium and other isotopes is highly radioactive, and some of it will remain so for thousands of years. Storage of this dangerous waste is a problem. The fission process also generates plutonium, which can be isolated to produce nuclear weapons, so the waste products could be a target for terrorists.

10.

The Earth's interior is heated by the decay of long-lived radioactive isotopes such as uranium and Thorium.

11.

Isotope	Mass (u)
H-1	1.007825
2 protons =	2.01565 u
2 neutrons =	2.01733 u

mass of 2 protons + 2 neutrons = 4.03298 u
mass of a helium nucleus = 4.0026 u
mass defect = 0.030377 u
binding energy = (0.030377 u)(931.5 MeV/u) = 28.29618 MeV released = 7.1 MeV/nucleon

To create helium (which has four nucleons) from hydrogen (which is one proton), would require four hydrogen joining. (The protons of two of the hydrogen would have to become neutrons by losing their charge. How this occurs is physics beyond this activity. The fusion process can be investigated by students as an additional exercise.) The mass defect of two neutrons and two protons is shown above to be 7.1 MeV per nucleon. (Numbers should both be on left-hand side of the element symbol and the positron.) A more detailed description is shown below.

Through a sequence of two-particle collisions,

$$p + p \rightarrow {}^{2}_{1}\mathrm{H} + \text{positron} + \text{neutrino},$$
$${}^{2}_{1}\mathrm{H} + p \rightarrow {}^{3}_{2}\mathrm{He} + \text{gammar-ray},$$
$${}^{3}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} \rightarrow {}^{4}_{2}\mathrm{He} + 2p,$$

the over-all effect is

$$4p \rightarrow {}^{4}_{2}\mathrm{He} + 2 \text{ positrons} + 2 \text{ neutrinos} + 2 \text{ gamma-rays} + \text{about } 25 \text{ MeV}$$

where the energy comes from the mass defect of the masses of the helium-4 nucleus plus two positrons (mass of positron = 0.000548597 u; the neutrino and gamma-ray photon have zero mass), compared to the masses of four individual protons.

12.

$$p + p \rightarrow {}^{2}_{1}\mathrm{H} + {}^{0}_{+1}e$$
$${}^{2}_{1}\mathrm{H} + p \rightarrow {}^{3}_{2}\mathrm{H}$$
$${}^{3}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} \rightarrow {}^{4}_{2}\mathrm{He} + 2p$$

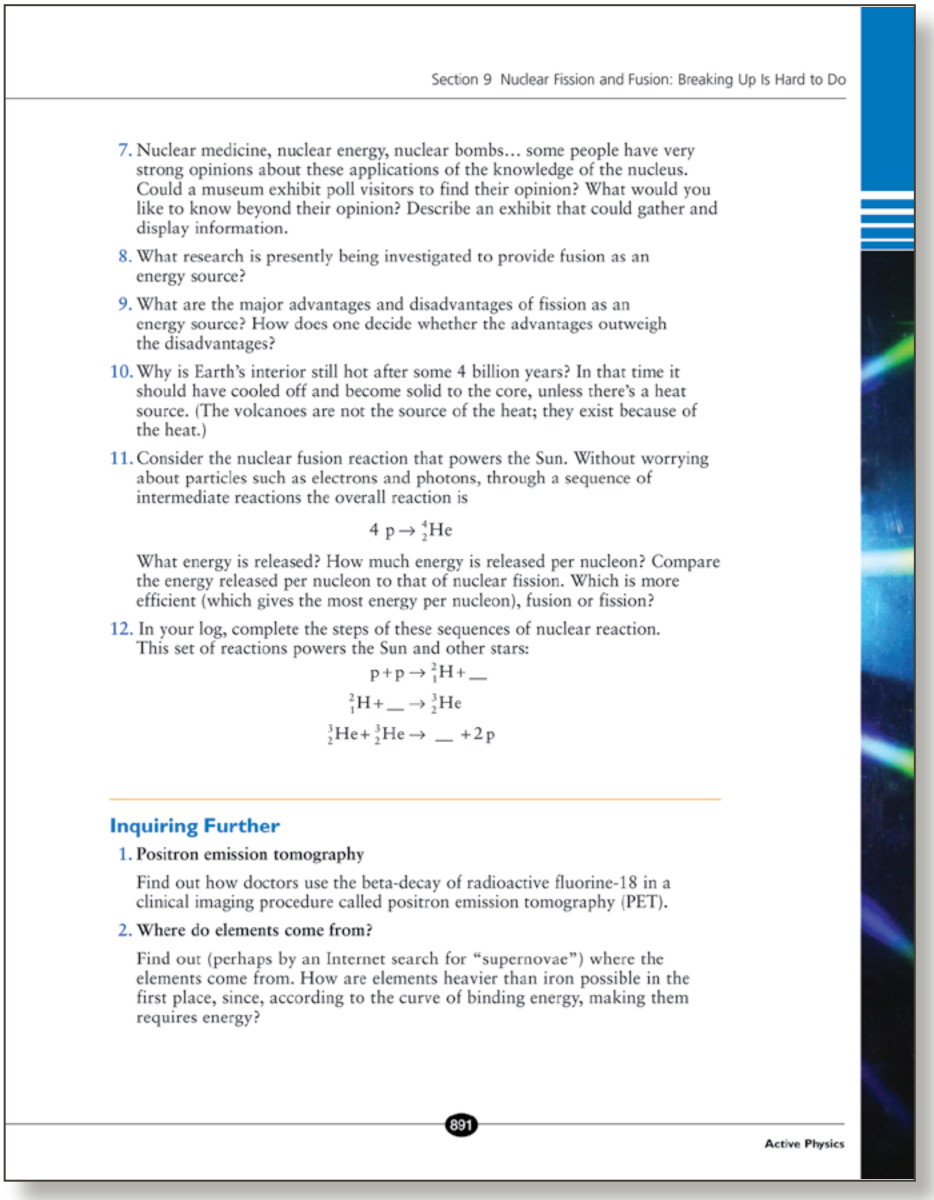
Inquiring Further

1.

PET scans are generally used to detect the uptake of glucose by tumors, which use glucose differently than normal tissue. Since tumors will concentrate the radioactively tagged glucose, they show up as "hot spots" when that area of the body gives off more radiation than other areas. These "hot spots" indicate the position and size of the tumor. The gamma radiation produced by the particle-antiparticle annihilation of the positrons emitted by the radioactive glucose are detected by a 3-D array, and computers are used to develop the image.

2.

Stars are able to produce atoms with atomic numbers up to iron by the fusion process and liberate energy to power the star. Typically, the heavier nuclei from Nitrogen through iron are produced in the last stages of the star's life, after it has passed through the hydrogen and helium "burning" phases. When the star has fused most of its hydrogen to form helium and nuclei such as carbon, the star starts to collapse.



Section 9 Nuclear Fission and Fusion: Breaking Up Is Hard to Do

7. Nuclear medicine, nuclear energy, nuclear bombs… some people have very strong opinions about these applications of the knowledge of the nucleus. Could a museum exhibit poll visitors to find their opinion? What would you like to know beyond their opinion? Describe an exhibit that could gather and display information.
8. What research is presently being investigated to provide fusion as an energy source?
9. What are the major advantages and disadvantages of fission as an energy source? How does one decide whether the advantages outweigh the disadvantages?
10. Why is Earth's interior still hot after some 4 billion years? In that time it should have cooled off and become solid to the core, unless there's a heat source. (The volcanoes are not the source of the heat; they exist because of the heat.)
11. Consider the nuclear fusion reaction that powers the Sun. Without worrying about particles such as electrons and photons, through a sequence of intermediate reactions the overall reaction is

$$4\,\mathrm{p} \rightarrow {}^{4}_{2}\mathrm{He}$$

What energy is released? How much energy is released per nucleon? Compare the energy released per nucleon to that of nuclear fission. Which is more efficient (which gives the most energy per nucleon), fusion or fission?

12. In your log, complete the steps of these sequences of nuclear reaction. This set of reactions powers the Sun and other stars:

$$\mathrm{p}+\mathrm{p} \rightarrow {}^{2}_{1}\mathrm{H} + \_\_$$

$${}^{2}_{1}\mathrm{H} + \_\_ \rightarrow {}^{3}_{2}\mathrm{He}$$

$${}^{3}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} \rightarrow \_\_ + 2\,\mathrm{p}$$

Inquiring Further

1. **Positron emission tomography**

   Find out how doctors use the beta-decay of radioactive fluorine-18 in a clinical imaging procedure called positron emission tomography (PET).

2. **Where do elements come from?**

   Find out (perhaps by an Internet search for "supernovae") where the elements come from. How are elements heavier than iron possible in the first place, since, according to the curve of binding energy, making them requires energy?

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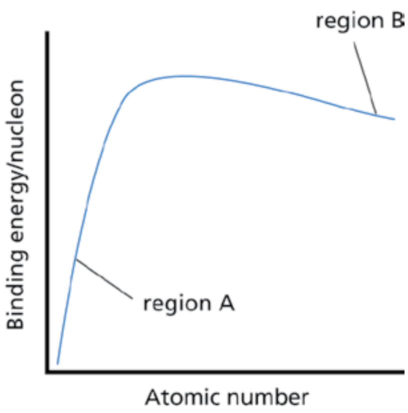
Active Physics

As it collapses, the interior temperature increases, allowing the star to fuse heavier elements up to iron. This is where some stars stop the element formation process.

Elements heavier than iron occur when very massive stars explode as part of their stellar cycle. Having passed through the previous stages up to forming iron, the stars go nova or supernova as the star undergoes a catastrophic collapse and rebounds to form the explosion. During this process, heavy nuclei, such as iron, are slammed together to form even heavier elements, all the up through uranium. These elements heavier than iron can only be formed during a supernova since that is the only time the nuclei would be moving fast enough to overcome their coulomb repulsion and fuse.

SECTION 9 QUIZ

8-9b **Blackline Master**



1. The diagram at right shows the binding energy / nucleon for the elements in the periodic table. Which statement below best describes how energy is released from elements in regions A and B?

   a) Region A releases energy by fission while region B releases energy by fusion.

   b) Region B releases energy by fission while region A releases energy by fusion.

   c) Both region A and B release energy by fusion.

   d) Both region A and B release energy by fission.

2. In nuclear reactors, to control the rate of fission, neutrons are absorbed by

   a) moderators. b) fuel rods.

   c) control rods. d) accelerators.

3. The equation ${}^{3}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + \text{energy}$ is an example of

   a) alpha decay. b) fusion.

   c) binding energy. d) fission.

4. Which equation represents nuclear fission?

   a) ${}^{214}_{82}\mathrm{Pb} \rightarrow {}^{214}_{83}\mathrm{Bi} + {}^{0}_{-1}\mathrm{e}$

   b) $4{}^{1}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + 2{}^{0}_{+1}\mathrm{e}$

   c) ${}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{138}_{56}\mathrm{Ba} + {}^{95}_{36}\mathrm{Kr} + 3{}^{1}_{0}\mathrm{n}$

   d) ${}^{234}_{92}\mathrm{U} \rightarrow {}^{230}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$

5. The main reason for using neutrons to bombard a nucleus is that neutrons

   a) have a relatively low atomic mass.

   b) have a very high kinetic energy.

   c) can be easily accelerated.

   d) are not repelled by the nucleus.

SECTION 9 QUIZ ANSWERS

1. b) Region B releases energy by fission as heavier nuclei are split into lighter ones to achieve a greater binding energy/nucleon. Likewise, region A releases energy by fusion as lighter nuclei combine to form heavier ones to increase the binding energy/nucleon.

2. c) control rods. Nuclear reactors use control rods to absorb neutrons and reduce the number of neutrons available to produce fission, slowing the reaction.

3. b) binding energy. The combining of light elements like isotopes of hydrogen to form heavier elements is the process of fusion. Alpha decay (answer a) also produces helium nuclei but does so by breaking apart a heavier nucleus into a lighter one and an alpha particle.

4. c) ${}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{138}_{56}\mathrm{Ba} + {}^{95}_{36}\mathrm{Kr} + 3\,{}^{1}_{0}\mathrm{n}$. Fission splits a heavier nucleus into two approximately equal pieces as in answer c). Answers a) and d) are examples of radioactive decay, and the major fragments after the reaction are not roughly equal in mass.

5. d) are not repelled by the nucleus. The reason neutrons are needed in fission reactions is that they are neutral and not repelled by the positively charged nucleus. This allows them to easily penetrate the nucleus and induce the fission reaction.