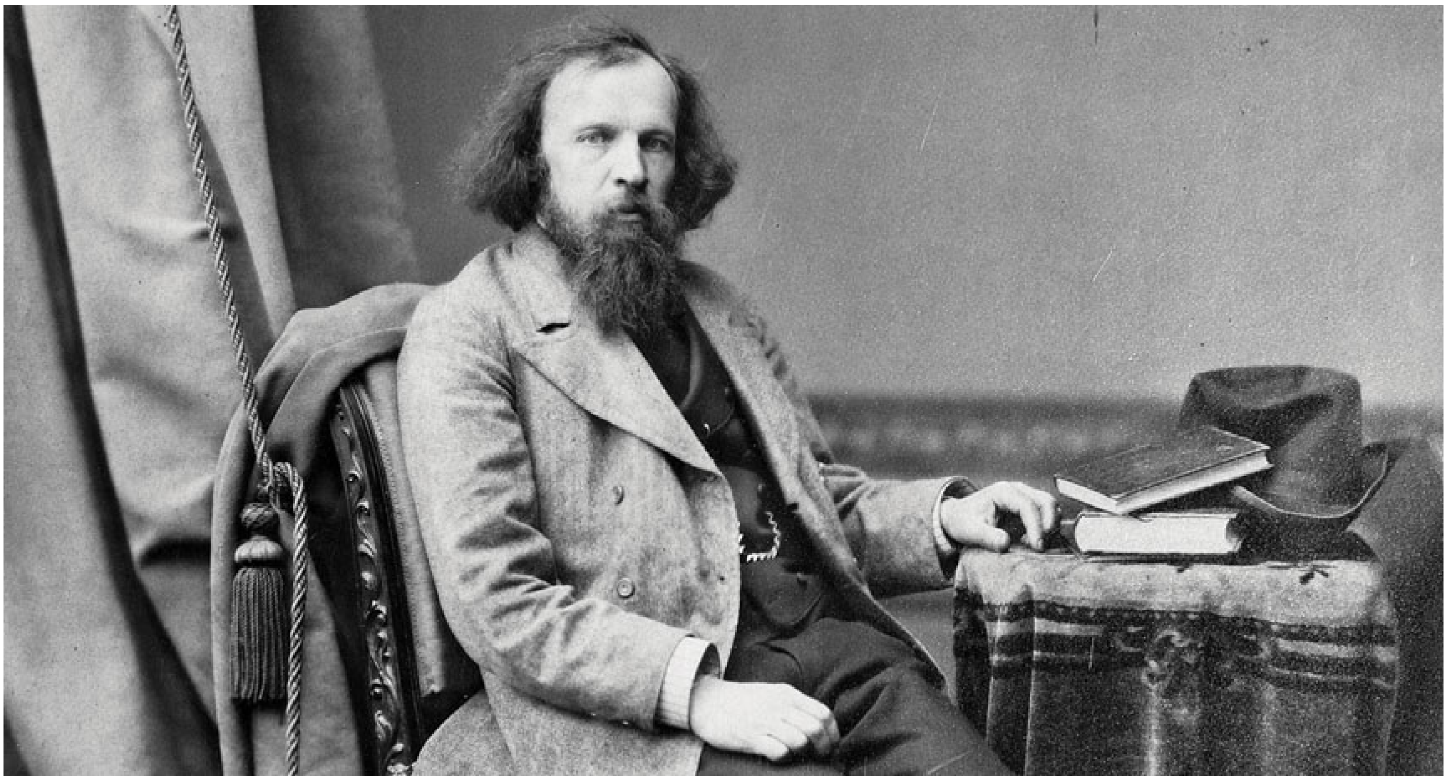
Science News
EDUCATOR GUIDE



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January 19, 2019
The Periodic Table Turns 150

SOCIETY FOR SCIENCE & THE PUBLIC

EDUCATOR GUIDE

January 19, 2019

The Periodic Table Turns 150

About this Guide

This year marks the 150th anniversary of the periodic table. Use this Guide to introduce students to the history and development of the periodic table, to the periodic table as a model and to scientific models more generally. Students will explore patterns in the arrangement of chemical elements on the table and patterns in the reactivity of those elements.

This Guide includes:

Article-based observation, Q&A — Students will answer questions based on the *Science News* article "The periodic table turns 150," Readability score: 11.2. Questions address the origin, development, predictive power and enduring value of the periodic table.

> **Article-based observations, questions only** — These questions are formatted so it's easy to print them out as a worksheet.

Cross-curricular connections, Q&A — After introducing the periodic table as a model, teachers can use these questions to lead a discussion about the principles and purposes of scientific models in all areas of science and engineering.

> **Cross-curricular connections, questions only** — These questions are formatted so it's easy to print them out as a worksheet.

Activity: Now Trending, the Periodic Table

> **Purpose:** After watching a video that introduces them to the periodic table, students will answer questions that prompt them to identify general patterns in the table. A second set of videos focused on reactivity will encourage students to use their observations to identify trends and predict behavior in reactivity among metals and nonmetals.
>
> **Approximate time:** 50 minutes

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Standards

Next Generation Science	Common Core ELA
Matter and its Interactions: HS-PS1-1, HS-PS1-2	Reading Informational Text (RI): 1, 2, 4, 5, 7
Energy: HS-PS3-1	Writing (W): 1, 2, 3, 4, 6, 7, 8, 9
Ecosystems: Interactions, Energy and Dynamics: HS-LS2-6	Speaking and Listening (SL): 1, 2, 4, 5, 6
Engineering Design: HS-ETS1-4	Reading for Literacy in Science and Technical Subjects (RST): 1, 2, 3, 4, 5, 7, 8, 9
	Writing Literacy in History/Social Studies and Science and Technical Subjects (WHST): 1, 2, 4, 7, 8, 9

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Article-Based Observation, Q&A

Directions: Ask students to answer the following questions based on the *Science News* article "The periodic table turns 150."

1. Before reading the article and based on your prior knowledge, what characteristics does the periodic table have? What is the periodic table's purpose?

The periodic table includes all the known elements and organizes the elements into rows and columns. It is ordered, concise and clear. The periodic table typically shows the elements' chemical symbols, atomic numbers and atomic weights. The table's purpose is to convey what the elements are, how they are related to one another and to provide some clues to how they behave. It is a useful guide for chemistry students and researchers.

2. Why, according to the article, is the anniversary of the periodic table a cause for celebration?

The periodic table is familiar to everyone. It concisely captures the elements that make up all earthly substances and their relationships. The periodic table reveals deep truths about chemistry and has played an important role in our understanding of the atom and in quantum theory. The birth and evolution of the periodic table is also an interesting story to tell.

3. What patterns did 19th century scientists — including John Dalton, Johann Wolfgang Döbereiner, John Newlands and Dmitrii Mendeleev — identify in the elements?

John Dalton suggested that elements were distinguished from each other by the weight of their atoms. German chemist Johann Wolfgang Döbereiner noticed that certain "triads" exist, in which three elements of increasing weight (such that one is the average of the other two) had similar chemical behaviors. John Newlands saw that arranging the elements in order of increasing atomic weight led to a recurring pattern in their chemical properties every eight elements. Dmitrii Mendeleev also noticed the relationship between atomic weight and chemical properties, but found that the pattern was a bit more complicated than Newlands had suggested.

4. Why did Dmitrii Mendeleev begin organizing elements? What other facts do you find interesting about Mendeleev's life?

Mendeleev began organizing the elements because he was writing a textbook for an inorganic chemistry class and he needed a way to organize the text. Among other interesting facts: He was the 17th child in his family. He nearly died from a serious illness during college. Along with a tutor and lecturer, he was a popular science writer and editor, translator and consultant to chemical industries. He won a cash prize by writing a handbook on organic chemistry.

5. Why does the author of the article call Dmitrii Mendeleev's original periodic table an "oracle"? Give an example to support your answer.

The organization of Mendeleev's table explained established chemical relationships so well that it was able to predict undiscovered elements, three of which were found in Mendeleev's lifetime. Mendeleev's table not only predicted the existence of the elements, but also their properties. For example, gallium was discovered in 1875, with an atomic weight of 69.9 and a density six times that of water. Mendeleev had predicted the element with the same density and an atomic weight of a very close 68.

6. Based on the text and the graphic on Page 15, name at least three differences between Mendeleev's original table and the table we use today.

Mendeleev's table was organized vertically and today's is organized horizontally. Mendeleev's table depended on ordering by atomic weight; today we order the elements by atomic number, or number of protons. Mendeleev's table did not include the noble gases or the transuranics or other synthetic elements. (Many elements have been discovered since Mendeleev's day.) Mendeleev's table did not have an element named after Mendeleev; today's table does.

7. What were the limitations of Mendeleev's original periodic table? How did these limitations affect Mendeleev's understanding of the patterns in his table?

Mendeleev's table was limited by current scientific knowledge. It included only 63 known elements. Many of the atomic weights were not yet certain. Because scientists didn't know what was in an atom, Mendeleev organized his table in general by atomic weight. But he had to add some exceptions to this ordering to get elements with similar chemical properties grouped together. Mendeleev also didn't know why his table worked; the underlying rules or facts that gave rise to the periodic behaviors remained a mystery.

8. How have atomic discoveries since Mendeleev's day informed our understanding the periodic table?

The discovery of electrons, the nucleus and protons revealed the subatomic structure of the atom and added clarity to the ordering of the elements, as well as explaining the recurring nature of chemical properties. Quantum theory deepened the understanding of electron arrangements and highlighted the importance of the outermost electrons in governing an element's behavior. A fuller understanding of atomic structure has led to the creation of synthetic elements. Though not discussed directly in the article, the discovery and explanation of radioactivity led to an understanding of isotopes and of the transmutation between elements.

9. Why do you think this article is labeled an "essay," and not a "feature" or "news" article?

Though the article depends on researched and reported facts, as do all of the articles in Science News*, the author takes a specific position — that the periodic table's creation is a cause for celebration and the periodic table has had an outsized role in scientific advancement. This is the thesis of the essay. The "essay" puts a finding in deeper context, including personal details, historical analysis, interpretation and commentary on existing knowledge. It also takes a less formal structure than a typical news article and offers novel insights by making connections to other areas of science.*

10. What lessons does the history and study of the periodic table offer to other fields of science, and the pursuit science more generally?

Much of science depends on finding patterns, order and structure in seeming chaos. This ordering often leads to rules that govern the world, and those rules can help scientists predict new features of the world, new *facts to be newly ordered. In this way, science progresses gradually. Science requires objective reasoning, of the kind Mendeleev applied when he sorted his note cards, and presupposes the existence of general principles, of causes and effects. The sciences are often built on classification — of elements, species, subatomic particles, cells — creating a shared language that yields a shared understanding. The periodic table was also built over time with contributions from many scientists, and is still being built today.*

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The Periodic Table Turns 150

Article-Based Observation, Q

Directions: Answer the following questions based on the *Science News* article "The periodic table turns 150."

1. Before reading the article and based on your prior knowledge, what characteristics does the periodic table have? What is the periodic table's purpose?

2. Why, according to the article, is the anniversary of the periodic table a cause for celebration?

3. What patterns did 19th century scientists — including John Dalton, Johann Wolfgang Döbereiner, John Newlands and Dmitrii Mendeleev — identify in the elements?

4. Why did Dmitrii Mendeleev begin organizing elements? What other facts do you find interesting about Mendeleev's life?

5. Why does the author of the article call Dmitrii Mendeleev's original periodic table an "oracle"? Give an example to support your answer.

6. Based on the text and the graphic on Page 15, name at least three differences between Mendeleev's original table and the table we use today.

7. What were the limitations of Mendeleev's original periodic table? How did these limitations affect Mendeleev's understanding of the patterns in his table?

8. How have atomic discoveries since Mendeleev's day informed our understanding the periodic table?

9. Why do you think this article is labeled an "essay," and not a "feature" or "news" article?

10. What lessons does the history and study of the periodic table offer to other fields of science, and the pursuit science more generally?

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Cross-Curricular Connections, Q&A

Directions: After using the *Science News* article "The periodic table turns 150" to review why the periodic table is considered a "model" in science, use the questions below to engage your class in a discussion about the principles and purposes of scientific models in all areas of science and engineering.

Suggestion for structuring discussion: Divide your class in half. Create either two lines or two concentric circles of students so that each student is facing a partner. Ask a question and allow students to answer the question with their partner. After the question is answered, direct students to rotate to a new partner. Once all questions are answered in pairs, ask students to return to their seats, and pick a few questions to review with the entire class.

Discussion background for the teacher: Dmitrii Mendeleev conceived the idea of the table by creating an organized system of known elements and used the organized system to predict the existence and properties of unknown elements. Mendeleev helped create one of the most notable and useful scientific models known today, the periodic table. When trying to explain some aspect of nature, developing systems and models is a common practice in all areas of science and engineering.

Discussion questions for students:

1. What is a system?

A system is an organized group of related components.

2. What is a model? Give an example of a model.

A model is generally thought of as an ideal representation of a concept, process or object, which is used to predict or explain an outcome. Meteorologists use models to predict the weather, and architects use models to plan and design urban structures.

3. What is a scientific model, and what is its purpose?

Scientific models are tools that organize a system so that it is well understood. The model can be used to predict and explain behaviors and outcomes of the system.

4. Are scientific models correct representations of natural phenomena? Explain.

Some models attempt to represent natural phenomena but are human inventions that are generally oversimplified and flawed. Models are often guided by a set of assumptions that minimize the numerous variables affecting the predicted behavior of the system.

5. How do models typically change over time?

As new technology guides experiments that test the validity of a scientific model, models are often "patched" or corrected over time. If a model is fixed a number of times, it can become more complicated. Sometimes a new model can take the place of a predecessor.

6. Apart from the periodic table, what is another scientific model that is discussed in the article? How is its development similar to that of the periodic table's?

The model of the atom is discussed toward the end of the article. Similar to the periodic table, the atomic model changed over time to accommodate experimental findings, such as Ernest Rutherford's discovery of the atomic nucleus, from the results of his gold foil experiment. Many scientists contributed to the creation and modification of both models over time.

7. Think about the different fields of science — chemistry, biology, environmental science, physics, genetics, and so on. What are some examples of other scientific models from these fields?

The plate tectonic model of the Earth can help predict geologic activity. Climate models are used to help predict weather patterns and how climates change. The biological evolutionary model explains how earlier species give rise to current species via natural selection. The wave-particle duality model of light (or the combination of the wave model and the particle model) can help predict the behavior of light. The ideal gas model allows a simplistic prediction of interactions in gaseous system based on a set of given conditions. Three-dimensional computerized models of proteins and protein receptors can help inform and assist drug design. Models of animal and plant populations can help predict ecological interactions and population dynamics.

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Cross-Curricular Connections, Q

Directions: Answer the questions below based on your teacher's instructions.

1. What is a system?

2. What is a model? Give an example of a model.

3. What is a scientific model, and what is its purpose?

4. Are scientific models correct representations of natural phenomena? Explain.

5. How do models typically change over time?

6. Apart from the periodic table, what is another scientific model that is discussed in the article? How is its development similar to that of the periodic table's?

7. Think about the different fields of science — chemistry, biology, environmental science, physics, genetics, and so on. What are some examples of other scientific models from these fields?

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Activity Guide for Teachers: Now Trending, the Periodic Table

Purpose: After watching a video that introduces them to the periodic table, students will answer questions that prompt them to identify general patterns in the table. A second set of videos focused on reactivity will encourage students to use their observations to identify trends and predict behavior in reactivity among metals and nonmetals.

Approximate time: 50 minutes

Supplies:

Activity Guide for Students

Handouts showing the periodic table or a large periodic table wall chart

Classroom computer projector to show video clips demonstrating chemical reactivity

Directions for teachers:

In the first part of this activity, students will get to know the periodic table through "The Periodic Table Song," various versions of which are available on YouTube. A new version of the song is at Periodic Table Song. Plan to play the song at least twice to get your students thinking about the table and its general set up. Allow students to listen generally once, then ask students to listen again and answer the questions provided. After the lesson, you could also share a classic version of the song by Tom Lehrer.

After students have completed the first set of questions, they will observe and predict trends in reactivity of metals and nonmetals based on the suggested videos below.

Have students create a data table to write down the physical properties of each metal element they will see in the video: lithium (Li), sodium (Na), potassium (K), magnesium (Mg), calcium (Ca) and strontium (Sr). Students should include space to make observations of each metal's reaction with water. Have students create a second data table to write down the physical properties of each nonmetal in the videos: chlorine (Cl), bromine (Br), iodine (I) and oxygen (O). Students should include space to make observations of each nonmetal's reaction with aluminum.

Play the following suggested videos or similar video clips and ask students to answer the questions that follow.

Suggested videos:

Alkali metals reacting with water

Chemistry of the group w elements (reactions with water)

Reactivity of halogens

Other optional videos:

[Reaction (explosion) of alkali metals with water]

[Mythbusters: Alkali metal explosion]

If you have the resources and equipment to safely do so, you could demo some of these reactions in the classroom. But even without a live demo, students should be able to make observations about the physical properties of the elements and observe trends in reactivity.

Directions for students: After listening to "The Periodic Table Song," answer the questions that follow.

1. What is the pattern you observe for the order in which the elements are presented during the song? List the first 12 elements mentioned in the song.

The periodic table is being read like a book: Elements are listed starting from the top, far left element (hydrogen) across the whole row before going down to the next row far left. The first 12 elements are: H, He, Li, Be, B, C, N, O, F, Ne, Na and Mg.

2. The atomic number defines the type of atom, or element, that exists. How does the number of protons, or the atomic number, differ from one element to the next in the song?

Each element mentioned has one more proton than the previous element mentioned.

3. What is the refrain of the song?

"This is the periodic table, noble gases stable, halogens and alkali react aggressively. Each period we'll see new outer shells, while electrons are added moving to the right."

4. What does the refrain tell you about the reactivity of noble gases? Where are noble gases located on the periodic table?

The rightmost column (noble gases) contains elements that have a stable configuration of electrons for each energy level, or row on the periodic table. Nobel gases do not generally give or accept any electrons, so they are nearly chemically inert.

5. Where are alkalies (metals) and halogens (nonmetals) located on the periodic table? Why do you think elements like the halogens and alkalies would react?

Alkali metals are in the leftmost column on the periodic table and halogens are to the left of the noble gases. Atoms in these columns react to become stable (have a lower energy state). Both the alkalies and the halogens react to become more like noble gases in terms of their number and configuration of electrons.

6. Given the long list of elements from the song, where do alkalies (metals) and halogens (nonmetals) always fall in relation to the closest noble gas in the list? How does the proximity to a noble gas affect how aggressively elements react?

Halogens are always the element before a noble gas and alkalies are always right after a noble gas. The closer the elements are to stability, the more aggressively they tend to react.

7. What does the refrain tell you will happen to the physical structure of the atoms as you go down a column, hopping from one period, or row, to the next? In your own words, what visual does the video use to show this trend?

The refrain says, "each period we'll see new outer shells." As you move down a column of the table, generally the element in the row below will have one more completely filled "shell" (energy level) of electrons than the one in the row above. The video shows a Bohr model of the atom, with a nucleus denoted by a red dot and shows electron shells being added as concentric circles, getting farther away from the nucleus.

8. What does the refrain tell you will happen to atoms as you go across a row, "moving to the right?" In your own words, what does the video use to show this trend?

The refrain says, "electrons are added moving to the right." As you move to the right across a row, generally the element to the right will have one more electron in the outermost electron shell (energy level) than the previous element. The video shows a Bohr model with a nucleus denoted by a red dot and shows electrons being added to existing concentric circles around the nucleus.

Directions for students continued: Before watching the videos on reactivity, create a data table to write down the physical properties of each metal element you will see in the video: lithium (Li), sodium (Na), potassium (K), magnesium (Mg), calcium (Ca) and strontium (Sr). Include space to make observations of each metal's reaction with water. Create a second data table to write down the physical properties of each nonmetal in the videos: chlorine (Cl), bromine (Br), iodine (I) and oxygen (O). Also, include space to make observations of each nonmetal's reaction with aluminum.

As you watch the videos, fill in your observation table based on what you observe. Then answer the questions that follow.

1. Based on your observations, list the metals in each of the following sets from least reactive to most reactive:

K, Na, Li

Li, Na, K

Sr, Ca, Mg

Mg, Ca, Sr

Na, Mg

Mg, Na

K, Ca

Ca, K

2. Based on your observations, list the following nonmetals from least reactive to most reactive:

Cl, Br, I

I, Br, Cl

3. Based on your observations and analysis, explain the general reactivity trend of metals as you go across a row from left to right on the periodic table. What about the trend as you go down a column on the periodic table?

Metals tend to get less reactive as you move across a period to the right and more reactive as you move down a column.

4. Based on your observations and analysis, explain the general reactivity trend of nonmetals as you go down a column on the periodic table?

Based on the reactivity trends of the halogens, nonmetals tend to be less reactive as you move down a column on the table.

5. In your experience with items made out of aluminum (aluminum cans, foil, etc.), how reactive is oxygen with aluminum? How do you think the reactivity of oxygen with aluminum would compare with the reactivity of fluorine with aluminum?

Aluminum reacts with oxygen over time, but it is a slow process. For example, an old aluminum can that has been sitting outside for a while can appear to have a rust-like layer on it. Based on the trend in nonmetal reactivity (the reactivity increases up a column), I would expect fluorine to be much more reactive with aluminum than oxygen would be with aluminum.

6. What do you predict is the general reactivity trend of nonmetals as you go across a row from left to right on the periodic table?

The reactivity of nonmetals would likely increase as you move across a period to the right.

7. What do you notice about the reactivity trends of metals compared with the reactivity trends of nonmetals?

The reactivity trends of metals are the opposite of the reactivity trends of nonmetals.

8. Atoms react to become more stable either losing or gaining (taking or sharing) electrons. Based on the proximity to a noble gas, do you think metals react by gaining or losing electrons? What about nonmetals?

Metals tend to lose electrons and nonmetals tend to gain electrons to become more stable (have an electron structure similar to a noble gas).

9. What patterns of reactivity would you expect from an element like silicon (Si)? Explain.

Silicon is the same number of elements away from the noble gas preceding it, Neon (Ne), as it is from the noble gas following it, Argon (Ar). It can probably gain or lose electrons to become stable, because it needs to gain or lose the same number of electrons to have a stable number (configuration) of electrons.

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Activity Guide for Students: Now Trending, the Periodic Table

Directions for students: After listening to "The Periodic Table Song," answer the questions that follow.

1. What is the pattern you observe for the order in which the elements are presented during the song? List the first 12 elements mentioned in the song.

2. The atomic number defines the type of atom, or element, that exists. How does the number of protons, or the atomic number, differ from one element to the next in the song?

3. What is the refrain of the song?

4. What does the refrain tell you about the reactivity of noble gases? Where are noble gases located on the periodic table?

5. Where are alkalies (metals) and halogens (nonmetals) located on the periodic table? Why do you think elements like the halogens and alkalies would react?

6. Given the long list of elements from the song, where do alkalies (metals) and halogens (nonmetals) always fall in relation to the closest noble gas in the list? How does the proximity to a noble gas affect how aggressively elements react?

7. What does the refrain tell you will happen to the physical structure of the atoms as you go down a column, hopping from one period, or row, to the next? In your own words, what visual does the video use to show this trend?

8. What does the refrain tell you will happen to atoms as you go across a row, "moving to the right?" In your own words, what does the video use to show this trend?

Directions for students continued: Before watching the videos on reactivity, create a data table to write down the physical properties of each metal element you will see in the video: lithium (Li), sodium (Na), potassium (K), magnesium (Mg), calcium (Ca) and strontium (Sr). Include space to make observations of each metal's reaction with water. Create a second data table to write down the physical properties of each nonmetal in the videos: chlorine (Cl), bromine (Br), iodine (I) and oxygen (O). Also, include space to make observations of each nonmetal's reaction with aluminum.

As you watch the videos, fill in your observation table based on what you observe. Then answer the questions that follow.

1. Based on your observations, list the metals in each of the following sets from least reactive to most reactive:

K, Na, Li

Sr, Ca, Mg

Na, Mg

K, Ca

2. Based on your observations, list the following nonmetals from least reactive to most reactive:

Cl, Br, I

3. Based on your observations and analysis, explain the general reactivity trend of metals as you go across a row from left to right on the periodic table. What about the trend as you go down a column on the periodic table?

4. Based on your observations and analysis, explain the general reactivity trend of nonmetals as you go down a column on the periodic table?

5. In your experience with items made out of aluminum (aluminum cans, foil, etc.), how reactive is oxygen with aluminum? How do you think the reactivity of oxygen with aluminum would compare with the reactivity of fluorine with aluminum?

6. What do you predict is the general reactivity trend of nonmetals as you go across a row from left to right on the periodic table?

7. What do you notice about the reactivity trends of metals compared with the reactivity trends of nonmetals?

8. Atoms react to become more stable either losing or gaining (taking or sharing) electrons. Based on the proximity to a noble gas, do you think metals react by gaining or losing electrons? What about nonmetals?

9. What patterns of reactivity would you expect from an element like silicon (Si)? Explain.

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Activity Guide for Teachers: The Periodic Table a Nuclear View

Purpose: Students will learn how interactions among the protons and neutrons in the atomic nucleus affect the properties and stability of chemical elements, and how these properties could inform the creation of future elements.

Procedural overview: After reviewing the semi-empirical mass formula as a class, students will apply the knowledge to calculate nuclear binding energies and to understand the formula's implications for nuclear reactions and nuclear decays.

Approximate class time: One class period.

Supplies:

Activity Guide for Students: The Periodic Table: A Nuclear View
Calculators (graphing calculators work best)
Optional: 3-D graphing program, such as Mathematica or Maple, and a computer projector

Directions for teachers:

Have your students read the article "Prospecting the periodic table," in the March, 2019 issue of *Science News*, and ask them to think about what a future periodic table might look like. Explain that the class period will be used to explore the properties of atomic nuclei, including equations that explain how the makeup of the nucleus and interactions among protons and neutrons affect its stability.

Plan to introduce the full semi-empirical mass formula on the board and use the class discussion questions below to review the meaning of the different terms in the formula with your students. Finally, have students explore patterns in nuclear stability by applying the semi-empirical mass formula to the student questions provided below.

If you have access to a 3-D graphing program such as Mathematica or Maple, show the students 3-D plots of the semi-empirical mass formula (plot $-E_B/A$ on the vertical axis vs. Z and N on the other axes), or even have the students make 3-D plots themselves.

Background information:

The electrons orbiting the atomic nucleus participate in chemical reactions and govern the properties of elements. The protons and neutrons within the atomic nucleus participate in nuclear reactions and govern the nuclear stability and other nuclear properties of elements. The protons and neutrons within the nucleus follow rules that are similar to those that electrons follow.

Protons and neutrons are collectively termed nucleons. The number of protons is Z, the atomic number. The number of neutrons is N. The atomic mass A is Z + N, not counting tiny fractions removed for the binding energy (see explanation below).

Nucleons within a nucleus have a lower total energy than free nucleons. The amount by which the energy of nucleons in the nucleus is lower is the binding energy E_B, which is defined here as a positive value (electron binding energies are measured in eV and nuclear binding energies are measured in MeV).

Since $E = mc^2$, if the energy of the nucleus decreases by E_B, the mass of the nucleus decreases by E_B/c^2. Nuclear reactions that change the binding energy can convert small fractions of the mass of the nucleus into relatively large amounts of energy.

The semi-empirical mass formula treats the nucleus as a collection of a large number of nucleons, so it is important to recognize that the resulting number is not very accurate for small nuclei, basically nuclei of the first six elements or so.

A simple version of the semi-empirical mass formula for the nuclear binding energy is:

E_B (in MeV) = $16(A) - 18(A)^{(2/3)} - 0.71(Z)(Z - 1)/(A)^{(1/3)} - 24(N - Z)^2/(A)$ + pairing term + shell correction

The pairing term:

if both N and Z are even numbers = $34(A)^{(-3/4)}$

if N is odd and Z is even, or vice versa (meaning A is odd) = 0

if both N and Z are odd numbers = $-34(A)^{(-3/4)}$

The shell correction is approximately A/20 if N or Z is a stable number (2, 8, 20, 28, 50, 82 or 126) for a completely filled shell.

The binding energy per nucleon is E_B/A. The larger that number is, the more stable the average nucleon is in a nucleus.

Class discussion questions:

1. The first term (16(A)) in the formula is the average binding energy of a nucleon with its nearest neighbors, due to the strong nuclear force. The strong force attracts protons and protons, neutrons and neutrons, and protons and neutrons, but it only acts at very short distances, basically for nearest neighbors. Often this first term is described as being proportional to the volume of the nucleus. Why does the nuclear volume increase in direct proportion to A?

Neglecting space between nucleons, if there are twice as many nucleons, the volume of the nucleus would be twice as large. So the volume of the nucleus is proportional to A. This relationship assumes that the number of nucleons is large enough that the nucleus can be treated as a large sphere of a given volume, not a lumpy shape of a handful of nucleons.

2. The second term $(-18(A)^{(2/3)})$ in the formula corrects for those nucleons at the surface of the nucleus that do not have nearest neighbors on one side. The term can also be thought of as a surface tension term, which pulls the nucleus into a spherical shape just as surface tension pulls water droplets into a spherical shape. Why is this term negative, and why is it proportional to $A^{(2/3)}$?

If the volume of the nucleus is proportional to the radius^3 or A, the surface area of the nucleus is proportional to radius^2 or $A^{(2/3)}$. The first term assumes that all nucleons have nearest neighbors on all sides, so it overestimates the binding energy. The second term is negative to subtract off that excess energy, in order to account for the fraction of nucleons that do not have nearest neighbors on one side.

3. The third term in the formula $(0.71(Z)(Z - 1)/(A)^{(1/3)})$, often called the Coulomb term, is due to the electric repulsion among the positively charged protons in the nucleus. Why is it negative? Why is it proportional to (Z)(Z - 1) and inversely proportional to $A^{(1/3)}$?

The strong force attraction among the nucleons makes the first term positive, but the electric repulsion among the protons opposes that, so the corresponding third term is negative. As the number Z of protons increases, the number of pairs of protons that repel each other increases like (Z)(Z - 1). *(The 1 is subtracted because a proton cannot repel itself.) The repulsive energy between a pair of protons is inversely proportional to the distance between them, and the average distance increases like the nuclear radius (volume$^{1/3}$),* $A^{(1/3)}$*, so the third term is inversely proportional to* $A^{(1/3)}$.

4. The fourth term in the formula $(-24(N - Z)^2/(A))$, often called the asymmetry term, acts to try to make the nucleus have equal numbers of protons and neutrons. Review how the Pauli exclusion principle and the Aufbau principle apply to electrons. The principles also apply to protons and neutrons. Why does the nucleus want to have approximately equal numbers of protons and neutrons and why is the fourth term negative?

From the Pauli exclusion and Aufbau principles, protons cannot occupy the same state as each other, so they occupy higher and higher energy levels. The same thing happens with the neutrons, except they are in their own set of energy levels. If there are equal numbers of protons and neutrons, they fill their respective set of energy levels up to the same level. If there are more neutrons than protons, they fill the neutron energy levels to a higher level than the proton energy levels. In this case, the neutrons at the highest filled levels are inclined to become protons (via beta decay) and thereby qualify to move to a lower energy level. (The same reasoning applies if there are more protons than neutrons.) The asymmetry term is negative because as |N - Z| increases, the excess neutrons (or excess protons) are increasingly unhappy to be stuck at higher and higher energies, so they are less tightly bound. Thus, the binding energy decreases.

5. Just considering the fourth term ($-24(N - Z)^2/(A)$) for a modest-sized atom with A = 24, how much energy would be released if the difference between neutrons and protons went from |N - Z| = 3, 2 or 1 to |N - Z| = 0? What does that suggest about the instability of certain nuclei and their likelihood to undergo beta decay?

For A = 24, going from |N - Z| = 3, 2 or 1 to |N - Z| = 0 would release $3^2 = 9$, $2^2 = 4$ or $1^2 = 1$ MeV, respectively. Deviating from the preferred balance between protons and neutrons rapidly decreases the binding energy, making those nuclei quite unstable and thus likely to undergo beta decay. That instability helps to explain why elements are predominantly made up of an isotope that is at or near balanced numbers of protons and neutrons, with few or no isotopes that deviate significantly from that balance.

6. The fifth or pairing term is positive if both N and Z are even, negative if both N and Z are odd and 0 otherwise. What does this mean physically?

The pairing term:

if both N and Z are even numbers = $34(A)^{(-3/4)}$

if N is odd and Z is even, or vice versa (meaning A is odd) = 0

if both N and Z are odd numbers = $-34(A)^{(-3/4)}$

The protons like to double up in pairs, with one spin-up and one spin-down. Likewise the neutrons like to double up in pairs, with one spin-up and one spin-down. The nucleus is happier (the binding energy is greater) if all the protons are in pairs and all the neutrons are in pairs. The nucleus is less stable (the binding energy is lower) if one proton is left unpaired and one neutron is left unpaired. The binding energy is intermediate if all the protons are paired but there is an unpaired neutron, or vice versa.

Student questions:

1. From examining the periodic table, what numbers of total electrons result in completely filled energy shells and therefore what are the most chemically stable elements?

From the last column of the period table, the numbers of total electrons that completely fill energy shells (and the corresponding elements) are 2 (He), 10 (Ne), 18 (Ar), 36 (Kr), 54 (Xe), 86 (Rn), etc.

2. There are also total numbers of protons that completely fill proton energy shells within the nucleus, and neutron totals that completely fill neutron energy shells. The stable numbers for protons or neutrons are different than those for electrons, since the forces within the nucleus are different. The numbers that result in stability, and high binding energy, for protons or neutrons are Z or N = 2, 8, 20, 28, 50, 82 and 126. Why do these number of protons and/or neutrons lead to stability? What elements and isotopes do the first three stable numbers (2, 8, 20) correspond to?

These numbers of protons and/or neutrons lead to stability because they completely fill shells within the nucleus. The first three stable numbers indicate that especially stable nuclei are helium-4 (Z = 2, N = 2), oxygen-16 (Z = 8, N = 8), and calcium-40 (Z = 20, N = 20).

3. The most stable nuclei (highest value of E_B/A) are those located around iron and nickel on the periodic table. What is E_B/A for iron-56?

E_B (in MeV) $= 16(56) - 18(56)^{(2/3)} - 0.71(26)(26 - 1)/(56)^{(1/3)} - 24(30 - 26)^2/(56) + 34(56)^{(-3/4)} + 0$

$E_B/(56) = 510$ MeV/56 = 9.1 MeV/nucleon

4. The semi-empirical mass formula is not designed to work well for very small nuclei, but for a rough estimate we can apply it to helium-4 and see what happens. What is E_B/A for helium-4?

E_B (in MeV) $= 16(4) - 18(4)^{(2/3)} - 0.71(2)(2 - 1)/(4)^{(1/3)} - 24(2 - 2)^2/(4) + 34(4)^{(-3/4)} + (4)/20$

$E_B/(4) = 30$ MeV/4 = 7.5 MeV/nucleon

5. The official value of E_B/A for helium-4 is approximately 7 MeV per nucleon. How close was your answer? Approximately how much energy would be produced by fusing four protons together to form helium-4, as occurs in stars? (Two of the protons become neutrons.)

For helium-4, the official value of 7 MeV/nucleon is close to the calculated value of 7.5 MeV. Protons are free nucleons so they have zero binding energy. Fusing them to produce helium-4 would yield 7 MeV/nucleon, or 28 MeV per helium-4 nucleus.

6. What is E_B/A for uranium-235? If the nucleons from a uranium-235 nucleus could split to form iron-56 nuclei, what would be the average energy released per nucleon, and the total energy released by the uranium nucleus? (In practice, 235 nucleons might divide up into nuclei that are somewhat larger or smaller than iron-56, but those new nuclei would have binding energies close to what you have already calculated for iron-56, so we will just use that.)

E_B (in MeV) $= 16(235) - 18(235)^{(2/3)} - 0.71(92)(92 - 1)/(235)^{(1/3)} - 24(143 - 92)^2/(235) + 0 + 0$

$E_B/A = 1850$ MeV/235 = 7.9 MeV

Going from uranium to iron would release 9.1 - 7.9 = 1.2 MeV/nucleon, or 1.2 MeV/nucleon x 235 nucleons/uranium = 280 MeV per uranium atom.

Note to the teacher: Uranium fission typically results in elements that are somewhat heavier and somewhat less tightly bound than iron, so it produces around 200 MeV per uranium atom. Without getting into those more detailed calculations, the simple calculation for students gives the right ballpark answer of 200-ish MeV per uranium atom.

7. What is E_B/A for a hypothetical new element with Z = 120 and N = 180? If the nucleons from an element 120 nucleus could split to form iron-56 nuclei, what would be the average energy release per nucleon, or the total energy released by element 120 nucleus? (In practice, 300 nucleons might divide up into nuclei that are somewhat larger or smaller than iron-56, but those new nuclei would have binding energies close to what you have already calculated for iron-56, so we will just use that.)

E_B (in MeV) = $16(300) - 18(300)^{(2/3)} - 0.71(120)(120 - 1)/(300)^{(1/3)} - 24(180 - 120)^2/(300) + 34(300)^{(-3/4)} + 0$

E_B/A = 2190 MeV/300 = 7.3 MeV

Going from element 120 to iron would release 9.1 - 7.3 = 1.8 MeV/nucleon, or

1.8 MeV/nucleon x 300 nucleons/atom = 540 MeV per atom.

Note to the teacher: As with uranium, the actual amount of energy released would be somewhat less, but this is still a very large amount of energy released and shows why such heavy elements are so unstable. If a heavy element can release around half a billion electron volts per atom by decaying, it will likely take the opportunity to get to a lower energy state.

8. Based on your calculations for uranium and element 120, what term in the semi-empirical mass formula makes nuclei increasingly unstable as they get very large? What is the physical explanation for that effect?

The third term, the Coulomb term, becomes a very large negative number, significantly decreasing the binding energy for very large nuclei. Physically, there are so many protons that the electric repulsion among them begins to overcome the nuclear strong force attraction among the protons and neutrons.

9. Maximizing E_B for a given value of A gives the optimal fraction of nucleons that should be protons in order to achieve the greatest stability with respect to beta decay. The following equation, which gives the optimal fraction, can be derived from the semi-empirical mass formula:

$Z/A = 0.5/(1 + 0.0074(A)^{(2/3)})$

For A = 16, what optimal fraction and number of protons does the equation predict? (Round your answer to a whole number.) What element is that?

Z/A = 0.48 or Z = 8, oxygen

10. For A = 235, what optimal fraction and number of protons does the equation predict? (Round your answer to a whole number.) What element is that?

Z/A = 0.39 or Z = 92, uranium

11. For A = 300, what optimal fraction and number of protons does the equation predict? (Round your answer to a whole number.) What element is that? From the "Long life" illustration in **"**Prospecting the periodic table,**"** for the optimal number of protons calculated, what N value might be the most stable? How does that compare with the N value when A = 300 and Z is the value calculated?

Z/A = 0.375 or Z = 113

According to the predicted island of stability, shown in the "Long life" illustration, ***if*** *Z = 113, the most stable values of N would be from about 183 to 186. The estimate landed in the right ballpark as an N value of 187 and right outside the information provided in the illustration. The complex nuclear forces in larger, heavier element also make it difficult to predict exactly where the hoped-for "island of stability" would be, or just how stable the elements on it would be.*

12. In general, what does this equation predict about protons and neutrons in light elements? What is the physical reason for that?

The numbers of protons and neutrons should be approximately equal, due to the asymmetry term.

13. In general, what does this equation predict about protons and neutrons in very heavy elements? What is the physical reason for that?

Neutrons should make up a larger and larger fraction of the nucleus. Extra neutrons are needed to provide extra strong force "glue" to overcome the increasing repulsion among the large numbers of protons.

14. What implications does this equation have for the composition and radioactivity of nuclei produced by fission reactions?

Stable forms of heavy nuclei such as uranium are very neutron-rich. When they split through fission, the resulting product nuclei will also be very neutron-rich. However, smaller nuclei do not like to be so neutron-rich, so they will be highly radioactive, undergoing lots of beta decay to convert some of their neutrons into protons.

15. What implications does this equation have for smashing smaller nuclei together as building blocks to create new very heavy elements?

New very heavy elements would need to be more neutron-rich than smaller nuclei would prefer to be. Thus it is difficult to find smaller nuclei that are sufficiently neutron-rich, or if you can find them, they rapidly undergo beta decay to be less neutron-rich, so you have to smash them together quickly before they decay. The article mentions that some of the experiments use calcium-48, a rare calcium isotope that has 20 protons but 28 neutrons. That makes it much more neutron-rich than normal calcium-40 (with just 20 neutrons). Whereas most smaller nuclei that are that neutron-rich would rapidly undergo beta decay, calcium-48 is unusually stable because it has stable numbers of both protons (Z = 20) and neutrons (N = 28).

The Periodic Table Turns 150

Activity Guide for Students: The Periodic Table a Nuclear View

Directions for students: After reviewing the semi-empirical mass formula as a class, answer the questions below. These questions ask you to calculate nuclear binding energies and to understand the formula's implications for nuclear reactions and nuclear decays.

Background information:

The electrons orbiting the atomic nucleus participate in chemical reactions and govern the properties of elements. The protons and neutrons within the atomic nucleus participate in nuclear reactions and govern the nuclear stability and other nuclear properties of elements. The protons and neutrons within the nucleus follow rules that are similar to those that electrons follow.

Protons and neutrons are collectively termed nucleons. The number of protons is Z, the atomic number. The number of neutrons is N. The atomic mass A is Z + N, not counting tiny fractions removed for the binding energy (see explanation below).

Nucleons within a nucleus have a lower total energy than free nucleons. The amount by which the energy of nucleons in the nucleus is lower is the binding energy E_B, which is defined here as a positive value (electron binding energies are measured in eV and nuclear binding energies are measured in MeV).

Since $E = mc^2$, if the energy of the nucleus decreases by E_B, the mass of the nucleus decreases by E_B/c^2. Nuclear reactions that change the binding energy can convert small fractions of the mass of the nucleus into relatively large amounts of energy.

The semi-empirical mass formula treats the nucleus as a collection of a large number of nucleons, so it is important to recognize that the resulting number is not very accurate for small nuclei, basically nuclei of the first six elements or so.

A simple version of the semi-empirical mass formula for the nuclear binding energy is:

E_B (in MeV) = $16(A) - 18(A)^{(2/3)} - 0.71(Z)(Z - 1)/(A)^{(1/3)} - 24(N - Z)^2/(A)$ + pairing term + shell correction

The pairing term:

if both N and Z are even numbers = $34(A)^{(-3/4)}$

if N is odd and Z is even, or vice versa (meaning A is odd) = 0

if both N and Z are odd numbers = $-34(A)^{(-3/4)}$

The shell correction is approximately A/20 if N or Z is a stable number (2, 8, 20, 28, 50, 82 or 126) for a completely filled shell.

The binding energy per nucleon is E_B/A. The larger that number is, the more stable the average nucleon is in a nucleus.

Questions:

1. From examining the periodic table, what numbers of total electrons result in completely filled energy shells and therefore what are the most chemically stable elements?

2. There are also total numbers of protons that completely fill proton energy shells within the nucleus, and neutron totals that completely fill neutron energy shells. The stable numbers for protons or neutrons are different than those for electrons, since the forces within the nucleus are different. The numbers that result in stability, and high binding energy, for protons or neutrons are Z or N = 2, 8, 20, 28, 50, 82 and 126. Why do these number of protons and/or neutrons lead to stability? What elements and isotopes do the first three stable numbers (2, 8, 20) correspond to?

3. The most stable nuclei (highest value of E_B/A) are those located around iron and nickel on the periodic table. What is E_B/A for iron-56?

4. The semi-empirical mass formula is not designed to work well for very small nuclei, but for a rough estimate we can apply it to helium-4 and see what happens. What is E_B/A for helium-4?

5. The official value of E_B/A for helium-4 is approximately 7 MeV per nucleon. How close was your answer? Approximately how much energy would be produced by fusing four protons together to form helium-4, as occurs in stars? (Two of the protons become neutrons.)

6. What is E_B/A for uranium-235? If the nucleons from a uranium-235 nucleus could split to form iron-56 nuclei, what would be the average energy released per nucleon, and the total energy released by the uranium nucleus? (In practice, 235 nucleons might divide up into nuclei that are somewhat larger or smaller than iron-56, but those new nuclei would have binding energies close to what you have already calculated for iron-56, so we will just use that.)

7. What is E_B/A for a hypothetical new element with Z = 120 and N = 180? If the nucleons from an element 120 nucleus could split to form iron-56 nuclei, what would be the average energy release per nucleon, or the total energy released by element 120 nucleus? (In practice, 300 nucleons might divide up into nuclei that are somewhat larger or smaller than iron-56, but those new nuclei would have binding energies close to what you have already calculated for iron-56, so we will just use that.)

8. Based on your calculations for uranium and element 120, what term in the semi-empirical mass formula makes nuclei increasingly unstable as they get very large? What is the physical explanation for that effect?

9. Maximizing E_B for a given value of A gives the optimal fraction of nucleons that should be protons in order to achieve the greatest stability with respect to beta decay. The following equation, which gives the optimal fraction, can be derived from the semi-empirical mass formula:

$Z/A = 0.5/(1 + 0.0074(A)^{(2/3)})$

For A = 16, what optimal fraction and number of protons does the equation predict? (Round your answer to a whole number.) What element is that?

10. For A = 235, what optimal fraction and number of protons does the equation predict? (Round your answer to a whole number.) What element is that?

11. For A = 300, what optimal fraction and number of protons does the equation predict? (Round your answer to a whole number.) What element is that? From the "Long life" illustration in "Prospecting the periodic table," for the optimal number of protons calculated, what N value might be the most stable? How does that compare with the N value when A = 300 and Z is the value calculated?

12. In general, what does this equation predict about protons and neutrons in light elements? What is the physical reason for that?

13. In general, what does this equation predict about protons and neutrons in very heavy elements? What is the physical reason for that?

14. What implications does this equation have for the composition and radioactivity of nuclei produced by fission reactions?

15. What implications does this equation have for smashing smaller nuclei together as building blocks to create new very heavy elements?

The Periodic Table Turns 150

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