Khan Academy

High School Chemistry

Unit 1: Atoms, isotopes, and ions

Overview

In this unit, students will begin to explore atomic structure and learn how atoms of different elements are similar to and distinct from each other.

Lesson 1: Students will **develop a model** of the atom based on the locations, relative masses, and charges of protons, neutrons, and electrons. Students will begin to recognize patterns and interpret and apply information available in the periodic table.

Lesson 2: Students will expand their model to include isotopes of the same element and will learn to write and interpret isotope notation. They will **use mathematics and computational thinking** to make inferences about the natural abundance of certain isotopes and to determine the average atomic mass of an element **from data**.

Lesson 3: Students will apply their atomic model to understand ion formation in terms of gain and loss of electrons.

Standards

Performance expectations: **HS-PS1-1**

Disciplinary core ideas: **HS-PS1.A.1 | HS-PS1.A.2**

Science and engineering practices:

- Developing and using models
- Using mathematics and computational thinking
- Analyzing and interpreting data

Crosscutting concepts:

- Systems and system models
- Structure and function
- Patterns
- Energy and matter

[Click here to read the full standards.]

Essential questions

- What are the relative masses and charges of protons, neutrons, and electrons, and where are they located in the electron cloud model of an atom?
- What makes the atoms of one element different from those of another element?
- What are isotopes, and how is the average atomic mass of an element determined?
- What causes an atom to have a positive or negative charge?

Lesson notes

Lesson 1: Atomic structure **PEs: HS-PS1-1** **DCIs: HS-PS1.A.1, HS-PS1.A.2**	**Resources** Video 2 · Exercise 2
Objectives	**Teaching tips**

• Label an electron cloud diagram of the atom showing the locations of **electrons**, **protons**, and **neutrons**.
• Compare the relative masses and charges of protons, neutrons, and electrons.
• Explain how the different types of **subatomic particles** determine the elemental identity and mass of an atom.
• Identify elements on the **periodic table** by their chemical symbols and **atomic numbers**.
• Determine the number of protons and electrons in a neutral atom of an element using the periodic table.
	• Engage students in a scaffolded exploration of basic atomic structure using the PhET Build an Atom simulation. Have students work in small groups, using the *Atom* section of the simulation to answer questions like the ones below. Ask students to provide evidence from the simulation to support their answers.
	  ○ Where is each subatomic particle located in the atom?
	  ○ What is the charge on each subatomic particle?
	  ○ Which subatomic particles affect the identity of an element?
	  ○ What determines the identity of an element?
	  ○ Which subatomic particles have the largest impact on the mass of an atom?
	  ○ When is an atom neutral?
	• Discuss students' discoveries from the simulation. Consolidate understanding by having students fill in a graphic organizer comparing the relative masses, charges, and locations in the atom of protons, neutrons, and electrons.
	• Provide students with their own copies of the periodic table that they can use throughout the course, and encourage them to annotate important information and patterns that are discussed. Various versions of the table showing different properties of the elements are available to download at PubChem.
	• Connect students' understanding of atomic structure to information available in the periodic table. Ask students to describe what they notice about the table in terms of the way it is organized and the information given. Ask students what they see inside each square in the table and if they notice any patterns as they look across a row or down a column.
	• Introduce a simple game to provide students with practice using the periodic table as a resource. Create a deck of index cards by writing one property of a different element on each card (chemical symbol, atomic number, number of protons, or number of electrons in a neutral atom). Students can take turns drawing cards and identifying the elements represented. Have them circle each element they identify on the periodic table, and the first student to get three elements in the same row or column of the table wins.

Lesson 2: Isotopes

PEs: HS-PS1-1
DCIs: HS-PS1.A.1

Resources

Video	Exercise
3	3

Objectives	Teaching tips

• Define **isotopes** and describe how isotopes of an element are the same and different in terms of atomic structure and properties.
• Determine the **mass number** for an isotope based on its elemental identity and number of neutrons, and represent it using **isotope notation**.
• Interpret isotope notation to identify the number of protons, neutrons, and electrons in a given isotope.
• Explain the difference between an isotope's mass number and an element's **average atomic mass** listed in the periodic table.
• Make inferences about the **relative abundance** of naturally occurring isotopes based on an element's average atomic mass and isotope mass numbers.
• Calculate the average atomic mass of an element from relative abundance and atomic mass data for its naturally occurring isotopes.
	• Revisit the [PhET Build an Atom] simulation. Have students work in small groups, using the *Symbol* section of the simulation to answer questions like the ones below. Ask students to provide evidence from the simulation to support their answers.
	  ○ What does each part of the atom's "symbol" in the simulation represent?
	  ○ How does the symbol for a hydrogen atom with zero neutrons differ from a hydrogen atom with two neutrons? How are they the same?
	  ○ How does the symbol for a helium atom with one neutron differ from a hydrogen atom with two neutrons? How are they the same?
	• Discuss students' discoveries from the simulation. Build on their learning by introducing the concept of isotopes and providing opportunities to practice writing and interpreting isotope notation.
	• Ensure that students develop a conceptual understanding of average atomic mass before asking them to carry out calculations. For example, have students estimate the average atomic mass of an element using the mass numbers of its isotopes and a pie chart of relative abundance data or using a mass spectrum of the element. Conversely, you can ask students to sketch a relative abundance pie chart or a mass spectrum based on an element's average atomic mass and the mass numbers of its isotopes.
	• Review how to represent a percent as a fraction or a decimal before using relative abundance to calculate average atomic mass.
	• When introducing average atomic mass as a "weighted" average, encourage students to recognize that *all* averages are "weighted." To help them understand why the equation for finding average atomic mass makes sense, ask students how they would find the average of three values. Students will likely say to add the values and divide by three. Use a simple example to show that this is the same as multiplying each value by one-third or by $0.\overline{3}$ and then adding them:
	$avg\ mass = \frac{(5.0\ g + 6.0\ g + 6.0\ g)}{3} = 5.7\ g$
	$avg\ mass = \frac{1}{3}(5.0\ g) + \frac{1}{3}(6.0\ g) + \frac{1}{3}(6.0\ g) = 5.7\ g$
	$avg\ mass = (0.\overline{3})(5.0\ g) + (0.\overline{3})(6.0\ g) + (0.\overline{3})(6.0\ g) = 5.7\ g$
	Point out that this calculation can be simplified to show that the value 6.0 g makes up two-thirds of the values. Since 6.0 g is *more abundant* in the data set, the average is closer to 6.0 g than 5.0 g:
	$avg\ mass = \frac{1}{3}(5.0\ g) + \frac{2}{3}(6.0\ g) = 5.7\ g$
	$avg\ mass = (0.\overline{3})(5.0\ g) + (0.\overline{6})(6.0\ g) = 5.7\ g$

	• To make the concept of average atomic mass less abstract, use samples with different kinds of beans to simulate samples of an element with several isotopes ("beanium"). Provide students with a sample and a balance. Ask them to sort the "isotopes," determine the relative abundance and the atomic mass of each "isotope," and then use their data to calculate the average atomic mass of the "element." An example of this process can be found in this video. • Provide more advanced learners with opportunities to extend their learning by exploring resources on the IUPAC Isotopes Matter website, including an interactive periodic table. • Ask students to consider how isotopic labeling can be used to ensure that fertilizers support crop growth without harming the environment. (*See the "Related phenomena" section below for more information.*)

Lesson 3: Ions

PEs: HS-PS1-1
DCIs: HS-PS1.A.1

Resources

Video	Exercise
2	2

Objectives	Teaching tips

• Explain how atoms form **anions** or **cations**, and determine the magnitude and sign of the charge on an **ion** based on its numbers of protons and electrons.
• Determine the numbers of protons and electrons in an ion from its chemical symbol and charge.
	• Revisit the PhET Build an Atom simulation. Have students work in small groups, using the *Atom* and *Symbol* sections of the simulation to answer questions like the ones below. Ask students to provide evidence from the simulation to support their answers.
	  ○ What is an ion?
	  ○ What makes an ion's charge negative? Positive?
	  ○ What determines an ion's *net charge*?
	• Discuss students' discoveries from the simulation. Ask them to use their learning to hypothesize why ions form by the gain or loss of electrons from an atom and NOT by the gain or loss of protons.
	• Invite students to play the *Game* in the simulation as a fun way to practice and apply their understanding of atomic structure from the last three lessons.
	• Alternatively, students can create their own game to quiz each other. Have students work in small teams to create questions on notecards or slides. Shuffle the cards or randomize the slides from all the teams, then play the game by having teams take turns answering questions. Prompt students to explain their reasoning in order to get full points for their answers.
	• Ask students to consider what causes a smoke detector alarm to sound. (*See the "Related phenomena" section below for more information.*)

Related phenomena

Example phenomenon

How can we ensure that fertilizers support crop growth without harming the environment?

Applying fertilizer to the soil

Background information

Isotopic labeling is a technique used to track the passage of an element through a chemical reaction, a metabolic pathway, or an ecological cycle. A substance is "labeled" by replacing some of its atoms with a much less abundant isotope of the same element. For example, water can be labeled by replacing some of its hydrogen-1 atoms with hydrogen-2 atoms or its oxygen-16 atoms with oxygen-18 atoms. This increases the relative abundance of the rare isotope in the water sample, compared to a naturally occurring sample. Scientists can determine how the labeled water interacts with other molecules in a cell or moves through an ecological cycle by testing samples from different parts of the process with mass spectrometry. Higher than normal ratios of H-2 to H-1 or O-18 to O-16 in the mass spectrum will indicate the presence of labeled water molecules or parts of these molecules.

A similar process can be used to analyze mineral absorption into the body from food or to study a new drug's metabolic pathway and its potential to accumulate in different body tissues. Isotopic labeling is also important for investigating the cycling of nitrogen through the atmosphere, soil, and waterways.

Nitrogen is an essential element for plant growth, which is why farmers add it to the soil through the application of fertilizers. Nitrogen-14 is the most abundant nitrogen isotope, making up 99.6% of naturally-occurring nitrogen, while Nitrogen-15 makes up only 0.37%. Labeling fertilizers with N-15 makes it possible to track what happens to the fertilizer after it is applied and where the nitrogen goes. These studies can determine how much nitrogen is taken up by plants, stays in the soil, escapes to the atmosphere (where it can form N_2O, a potent greenhouse gas), or moves into waterways (where it can have negative effects on aquatic ecosystems). Researchers can use their findings to make recommendations to farmers about sustainable practices that support crop growth and also protect the environment.

Exploring this phenomenon helps students develop and master the following understandings:

- ☐ Isotopes are atoms of the same element with different numbers of neutrons that can be distinguished by their different atomic masses.
- ☐ The relative abundance of an isotope is the percentage of atoms with a specific atomic mass found in a naturally occurring sample of an element.
- ☐ Mass spectrometry can be used to determine the relative abundance of each isotope in a sample.

Tips for implementing phenomenon-based learning

- Ideas to encourage student engagement:
  - Ask students to write the isotope notation for relevant isotope pairs used in isotopic labeling, such as H-2 and H-1, O-18 and O-16, and N-15 and N-14. Then, ask them to determine the number of protons, neutrons, and electrons in a neutral atom of each isotope.
  - Provide students with the mass spectrum for a naturally occurring sample of nitrogen atoms,

and ask them to analyze it by explaining what information is shown. Then, have students sketch how the mass spectrum of an N-15 labeled sample would look different. The Prot pi Mass Spectrum Simulator tool can be used to generate a simulated mass spectrum of any element.

- Have students work in pairs or small groups to research one part of the nitrogen cycle. This video and this article from Khan Academy provide a helpful starting point. Assign a different part of the cycle to each group, and ask students to develop a labeled model explaining where the nitrogen comes from, where it goes, and how it changes forms. Have students present their models to each other and discuss how they intersect.
- If students are interested in exploring the impact of human activities on nitrogen levels in different parts of the cycle and the effects of these changes on ecosystems, use this video and this article from Khan Academy to kick-start conversation.
- Invite a guest speaker who works in fertilizer development or a related field of agricultural research to talk with the class in person or via videoconference.

- Sample prompts to elicit student ideas and encourage discussion:
  - How are atoms of N-15 and N-14 the same, and how are they different? How could you distinguish between them experimentally?
  - Why is N-15, rather than N-14, used to track plants' nitrogen uptake?
  - How can testing for the presence of N-15 in local waterways alert farmers to runoff and pollution issues?
  - What other processes or cycles that you've learned about previously could be monitored using isotopic labeling?

Example phenomenon

What causes a smoke detector alarm to sound?

Background information

Smoke detector with smoke

Ionization smoke detectors, one of the most common types of smoke detectors found in homes, rely on a small amount of a radioactive isotope to ionize molecules in the air.

The detector contains an ionization chamber with two electrically charged plates connected to the positive and negative ends of a battery and separated by air. A tiny sample (about 0.0002 g) of americium-241 inside the chamber emits alpha particles, which are helium-4 ions with a 2+ charge. These alpha particles hit oxygen and nitrogen molecules in the air and ionize them by knocking off electrons. The free electrons then attach to other neutral molecules. The resulting cations and anions are attracted to the oppositely charged plates. As cations move toward the negatively charged plate and anions move toward the positively charged plate, a small electric current is able to travel from one plate to the other, completing the circuit.

When smoke particles enter the chamber, they attach to the ions and disrupt their flow between the plates, which reduces the electric current. The device senses this change in the current, and the alarm sounds.

Exploring this phenomenon helps students develop and master the following understandings:

- ☐ Isotopes are atoms of the same element with different numbers of neutrons.
- ☐ Isotope notation can be used to represent the mass number, atomic number, and charge of an atom.
- ☐ A neutral atom forms a positive ion (cation) by *losing* negatively charged electrons. A neutral atom forms a negative ion (anion) by *gaining* negatively charged electrons.
- ☐ Oppositely charged particles attract and particles with the same charge repel.

Tips for implementing phenomenon-based learning

- Ideas to encourage student engagement:
    - Ask students to write the isotope notation for americium-241 (the source of the ionizing radiation) and for a helium-4 atom that has lost two electrons (an alpha particle). Have students determine the number of protons, neutrons, and electrons present in each one. *Note: a detailed discussion of the nuclear decay process by which Am-241 isotopes emit alpha particles may be saved for later, once students have a stronger grasp of atomic structure and chemical reactions. Return to this phenomenon in Unit 10: Nuclear chemistry.*
    - Give students a simple diagram of an ionization chamber, showing the two charged plates with positively and negatively charged particles in between. Ask students to draw arrows showing the directions in which the particles will move and to explain their reasoning. For a hands-on investigation of attractive and repulsive forces between charged objects, use a simple "sticky tape" activity, like this one from NASA.
    - Ask students to create a public service announcement (PSA) explaining how an ionization smoke detector works and why it is important to test the ones in your home regularly. This could take the form of a physical or digital poster or a short video that they can share with classmates and family members. Require that students correctly define and use the following terms in their PSA: *proton*, *neutron*, *electron*, *isotope*, *mass number*, *anion*, and *cation*.
- Sample prompts to elicit student ideas and encourage discussion:
    - What makes an "alpha particle" a helium ion?
    - How do the oxygen and nitrogen molecules in the air inside the smoke detector become charged? (*Follow up:* Why are electrons, rather than other subatomic particles, knocked off of the molecules?)
    - Which charged plate would attract the cations? Which charged plate would attract the anions? What is a general rule for attractive (and repulsive) forces between charged objects?
    - Sometimes, a smoke detector goes off when we accidentally burn something while cooking. To get the alarm to stop sounding, we might wave a dish towel or magazine underneath the detector. Why does this work?

Common student misconceptions

Possible misconception: *All atoms of an element must be identical and share the same properties.*

When students are introduced to the idea that everything in the universe is composed of atoms, they often learn that different types of atoms represent elements with unique sets of physical and chemical properties. This may lead students to believe that all atoms of a given element must have fundamentally identical properties and that any changes to an atom's structure will necessarily change its elemental identity.

Critical concepts

- An atom's elemental identity is defined by the number of protons in its nucleus.
- When an atom becomes charged, it gains or loses electrons, but the number of protons remains the same, so its elemental identity does not change.
- Isotopes are atoms of the same element (same number of protons) with different numbers of neutrons in their nuclei, resulting in different atomic masses.

How to address this misconception

Establish early on that the number of protons in an atom's nucleus, its atomic number, is what defines its elemental identity. Emphasize that this is why elements are listed by atomic number in the periodic table—because atomic number is unique to each element. Encourage students to explore the PhET Build an Atom simulation to see what happens to the elemental identity of an atom when they change the number of each type of subatomic particle. This will provide evidence that atoms of the same element can have different numbers of electrons and neutrons and, therefore, can vary in charge and mass.

Possible misconception: *Protons can be lost or gained during ionization.*

When students learn that an imbalance of protons and electrons causes an atom to become charged, they may believe that a loss or gain of *protons*, rather than electrons, could be responsible. For example, students may think that positive ions can form when an atom gains positively charged protons or that negative ions form when an atom loses positive charge by losing protons.

Critical concepts

- Protons, along with neutrons, are located in the nucleus at the center of the atom, while electrons are located in a "cloud" outside the nucleus.
- The number of protons in an atom's nucleus is what defines its identity as a particular element and does not change when an atom becomes charged.
- A neutral atom forms a positive ion (cation) by *losing* negatively charged electrons. A neutral atom forms a negative ion (anion) by *gaining* negatively charged electrons.

How to address this misconception

Ask students to observe an electron cloud model of the atom and note the locations of the protons and electrons. Ask them to infer which type of subatomic particle will be most easily added to or removed from an atom based on its location. Emphasize that the electrons, due to their location on the outer edge of the atom, are the particles gained or lost when atoms form ions. Protons, located in the center of the atom, stay in the nucleus and maintain the atom's elemental identity during ionization. Encourage students to explore this phenomenon using the PhET Build an Atom simulation.

Unit resources

Student resources

- PhET Build an Atom: Use this simulation for a virtual investigation of atomic structure and isotope notation.
- Converting percents to decimals & fractions example: Review how to represent a percent as a fraction or a decimal with this Khan Academy video.
- IUPAC Isotopes Matter: Extend learning about isotopes with resources from this website.
- The nitrogen cycle (video) and The nitrogen cycle (article): Learn about the nitrogen cycle with these Khan Academy resources..
- Impacts of agricultural practices (video) and Human impacts on biogeochemical cycles (article): Learn about the impact of human activities on nitrogen levels in the environment and the effects of these changes on ecosystems with these Khan Academy resources.
- Article and video note taking template (Doc | PDF): Use this printable template for structured note taking on the articles and videos in this unit.

Classroom implementation resources

- Prot pi Mass Spectrum Simulator: Use this tool to generate a simulated mass spectrum of any element.
- PubChem Periodic Table of Elements and Printable Periodic Tables: Download various versions of the periodic table, including a blank template.
- Weekly Khan Academy quick planning guide (Doc | PDF): Use this template to easily plan your week.
- Using Khan Academy in the classroom (Doc | PDF): Learn about teaching strategies and structures to support your students in their learning with Khan Academy.
- Differentiation strategies for the classroom (Doc | PDF): Read about strategies to support the learning of all students.
- Using phenomena with the NGSS: Learn more about how to incorporate phenomena into NGSS-aligned lessons.
- Hands-on science activities from Khan Academy: Choose from Khan Academy's collection of high-quality, ready-to-use, and free hands-on science activities. Each one is engaging, three-dimensional, phenomenon-based, and simple to implement.

NGSS standards reference guide

Performance expectations

- **HS-PS1-1:** Use the periodic table as a model to predict the relative properties of elements based on the patterns of electrons in the outermost energy level of atoms.

Disciplinary core ideas

- **HS-PS1.A.1:** Each atom has a charged substructure consisting of a nucleus, which is made of protons and neutrons, surrounded by electrons.
- **HS-PS1.A.2:** The periodic table orders elements horizontally by the number of protons in the atom's nucleus and places those with similar chemical properties in columns. The repeating patterns of this table reflect patterns of outer electron states.

Science and engineering practices (SEPs)

- **Developing and using models**: Students progress to using, synthesizing, and developing models to predict and show relationships among variables between systems and their components in the natural and designed worlds.
- **Using mathematics and computational thinking:** Students progress to using algebraic thinking and analysis, a range of linear and nonlinear functions including trigonometric functions, exponentials and logarithms, and computational tools for statistical analysis to analyze, represent, and model data. Simple computational simulations are created and used based on mathematical models of basic assumptions.
- **Analyzing and interpreting data:** Students progress to introducing more detailed statistical analysis, the comparison of data sets for consistency, and the use of models to generate and analyze data.

Crosscutting concepts (CCCs) and their implementation

Crosscutting concept	Unit implementation
Systems and system models: Defining the system under study—specifying its boundaries and making explicitly a model of that system—provides tools for understanding and testing ideas that are applicable throughout science and engineering.	Students define and describe different models of atoms.
Structure and function: The way in which an object or living thing is shaped and its substructure determine many of its properties and functions.	Students connect atomic structure to elemental identity and properties of matter.
Patterns: Observed patterns of forms and events guide organization and classification, and they prompt questions about relationships and the factors that influence them.	Students identify patterns in the periodic table related to atomic structure and elemental properties.
Energy and matter (Flows, cycles, and conservation): Tracking fluxes of energy and matter into, out of, and within systems helps one understand the systems' possibilities and limitations.	Students consider the movement of subatomic particles into or out of the atom.