Chemistry

A Guided Inquiry

Seventh Edition

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CHEMISTRY

A Guided Inquiry

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To the Instructor

The activities in this book are written according to the principles of Process Oriented Guided Inquiry Learning (POGIL), a student-centered, team-based, active-learning pedagogy based on research on how students learn best. POGIL activities are designed to be used by students as active participants in learning teams. There are many written materials available on-line to help instructors use this particular collection of POGIL activities effectively. Please contact your Wiley representative for information on how to obtain access to these materials, or visit the web site at:
http://www.wiley.com/college/moog.

In addition, The POGIL Project supports the dissemination and implementation of these types of materials for high school chemistry courses at the first-year and AP levels and for most of the undergraduate chemistry curriculum (including organic, physical, analytical and biochemistry.) POGIL materials are also available for other STEM disciplines including biology and anatomy and physiology, materials engineering, computer science, and mathematics. Information about The POGIL Project, a not-for-profit 501(c)(3) organization, and its activities (including additional materials, workshops, and other professional development opportunities) can be found at http://www.pogil.org.

New for this edition

This 7th edition of *Chemistry: A Guided Inquiry* is the result of the most substantial changes that we have made to these activities since they were first published over twenty years ago. Over the past several years, substantial gains have been made by a variety of colleagues in The POGIL Project – and others – in understanding how to create activities that produce the most learning and the greatest gains in the development of key learning skills such as teamwork, critical thinking, and problem solving. We have tried to incorporate as much of these new insights into the structure and organization of these materials as we can.

Below we list some of the major changes and highlights for this new edition:

- Several activities have been restructured to better incorporate a learning cycle structure of exploration, concept invention, and application.
- Many of the activities now begin with a "Warm-Up" section that students *may* complete before coming to class. In many cases, the activity has been reorganized so that much of the text is now in this "Warm-Up" section, enabling students to read some introductory material before coming to class and reserving more class time for working on the activities with their teammates. Instructors may choose to use the "Warm-Up" sections in this way, or they may choose to have the students complete the "Warm-Up" sections as part of the team work during class time.
- The amount of text has been reduced and restructured to make it easier for students to read and process.
- Student responses to Critical Thinking Questions are more frequently organized into tables to facilitate analysis and interpretation.
- The content dealing with electronegativity, partial charge, and dipole moments has been reorganized to reduce repetition and get to the concept of electronegativity sooner. The concept of Average Valence Electron Energy is still introduced (in ChemActivity 19) but its relationship to electronegativity is then established directly.
- Based on research on how students respond to the wording of prompts in these types of activities, we have included more prompts that directly require the students to explain their reasoning and/or analysis. We have also included more explicit prompts for students to engage as a team in addressing the questions that are posed.

Acknowledgments

This book is the result of innumerable interactions that we have had with a large number of stimulating and thoughtful people.

- We greatly appreciate the support and encouragement of the many members of The POGIL Project and the Middle Atlantic Discovery Chemistry Project, who have provided us with an opportunity to discuss our ideas with interested, stimulating, and dedicated colleagues. Over the past several years, our colleagues in The POGIL Project have helped us learn a great deal about how to construct more effective and impactful activities; much of what we have learned from them is reflected in the substantially revised activities in this edition.

- Thanks to the numerous colleagues who used our previous editions in their classrooms. Many provided us with insightful comments and suggestions for which we are grateful. We are particularly indebted to Professor Gail Webster, Guilford College, who provided us with feedback on every activity in this edition. Her thoughtful insights and suggestions had a significant impact on the final product.

- Many thanks to Jim Spencer, Professor Emeritus, Franklin & Marshall College, for his helpful and insightful discussions, comments, and corrections.

- A great debt of thanks is due our students in General Chemistry at Franklin & Marshall College over the past two decades. Their enthusiasm for this approach, patience with our errors, and helpful and insightful comments have inspired us to continue to develop as instructors, and have helped us to improve these materials immeasurably. In particular, RSM thanks the students in his CHM 111 class at Franklin & Marshall College who used the penultimate draft of this book during the fall, 2016 semester. Their thoughtful comments and keen eye for typographic errors helped improve this edition and their patience and good humor was greatly appreciated.

- Thanks to the National Science Foundation (Grants DUE-0231120, 0618746, 0618758, and 0618800) for its initial support of The POGIL Project, a not-for-profit organization that fosters the development and dissemination of guided-inquiry materials and encourages faculty to develop and use student-centered approaches in their classrooms.

- Special thanks to Dan Apple, Pacific Crest Software, for starting us on this previously untraveled path. The Pacific Crest Teaching Institute we attended in 1994 provided us with the initial insights and inspiration to convert our classrooms into fully student-centered learning environments.

- RSM would also like to thank Mark McDaniel, Gina Frey, and all of the staff of the Center for Integrative Research on Cognition, Learning, and Education at Washington University in St. Louis. A more stimulating sabbatical year could not be imagined, and many of the insights gained from that year were invaluable in improving this edition.

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To the Student

Science and engineering have dominated world events and world culture for at least 150 years. The blind and near blind have been made to see. The deaf and near deaf have been made to hear. The ill have been made well. The weak have been made strong. Radio, television and the internet have made the world seem smaller. And some of us have left the planet. Computers have played an essential role in all of these developments; they are now ubiquitous. These miraculous events happened by design—not by accident. Individuals and teams set out to accomplish goals. They systematically studied and analyzed the natural world around us. They designed and tested new tools. Human beings have embarked on a journey that cannot be reversed. We hope that you can participate in and contribute to these exciting times.

There is simply too much chemistry—not to mention physics, mathematics, biology, geology, and engineering—for any one person to assimilate. As a result, teams have become essential to identifying, defining, and solving problems in our society. This book was designed for you to use as a working member of a team, actively engaged with the *important basic* concepts of chemistry. Our goals are to have you learn how to examine and process information, to ask good questions, to construct your own understanding, and to build your problem-solving skills.

If ever a book was written for students—this is it. This is *not* a textbook. This is *not* a study guide. This book is "a guided inquiry," in which you will examine data, written descriptions, and figures to develop chemical concepts. Each concept is explored in a *ChemActivity* comprising several sections—one or more **Model** and **Information** sections, **Critical Thinking Questions**, and **Exercises** and **Problems**. You and your team study the Models and Information and systematically work through the Critical Thinking Questions. In doing so, you will discover important chemical principles and relationships. If you understand the answer to a question, but other members of your team do not, it is your responsibility to explain the answer. Explaining concepts to other members of your team not only helps in *their* understanding, it broadens *your* understanding. If you do not understand the answer to a question, you should ask one or more *good* questions (to the other members of your team). Learning to ask questions that clearly and concisely describe what you do not understand is an important skill. This book has many Critical Thinking Questions that serve as examples. To reinforce the ideas that are developed, and to practice applying them to new situations, numerous Exercises and Problems are provided; these are important for you to apply your new knowledge to new situations and solidify your understanding. Research has demonstrated that this combination of methods is generally a more effective learning strategy than the traditional lecture, and the vast majority of our students have agreed.

We hope that you will take ownership of your learning and that you will develop skills for lifelong learning. Nobody else can do it for you. We wish you well in this undertaking.

If you have any suggestions on how to improve this book, please contact us.

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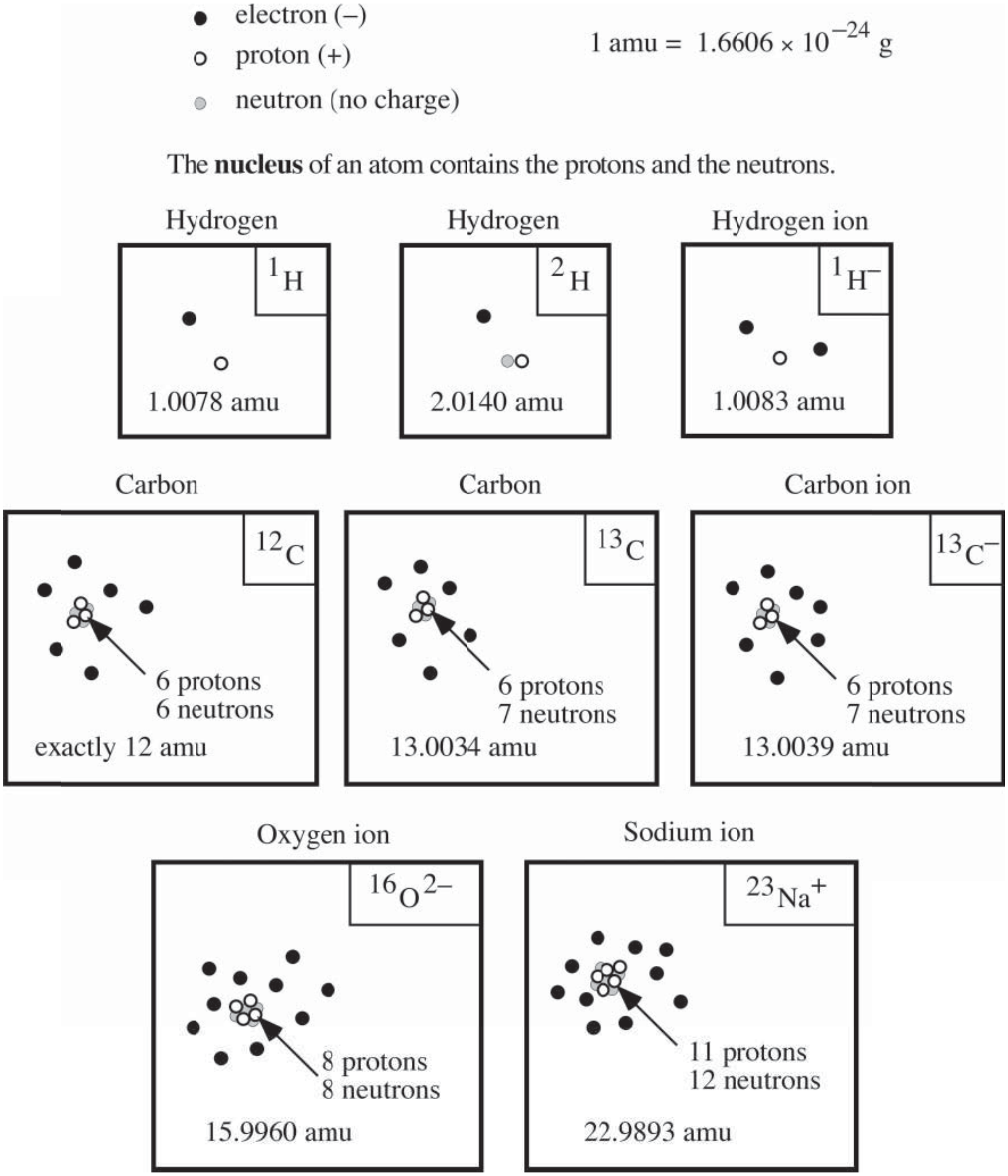
ChemActivity 1

The Nuclear Atom

(What Is an Atom?)

Model: Schematic Diagrams for Various Atoms and Ions.



1 amu = 1.6606×10^{-24} g

The **nucleus** of an atom contains the protons and the neutrons.

^{1}H and ^{2}H are **isotopes** of hydrogen.

^{12}C and ^{13}C are **isotopes** of carbon.

Critical Thinking Questions

1. Write the symbols for the four ions in the Model.
2. Write the symbols for the four uncharged atoms in the Model.
3. Individually, complete the following table using information from the Model. Then discuss your answers as a team and reach a consensus on all of the entries.

	# of protons	# of neutrons	# of electrons	charge
^{12}C				0
^{13}C				0
$^{13}C^-$				-1

4. How did your team determine the table entries for each of the following table columns from the Model?
   a) number of protons
   b) number of neutrons
   c) number of electrons
5. a) Based on the completed table in CTQ 3, what do all carbon atoms (and ions) have in common?

   b) Explain how your team reached a conclusion for part a by specifically referring to information from the completed table in CTQ 3.

6. a) Complete the following table using information from the Model.

	# of protons	# of neutrons	# of electrons	charge
^{1}H				
^{2}H				
$^{1}H^-$				

   b) Based on the model and the answers to part a above, what do all hydrogen atoms (and ions) have in common? Explain your reasoning.

7. Locate the atomic symbols for carbon and hydrogen in a periodic table. There is a number above each symbol in the periodic table, called the **atomic number**. Based on your answers to CTQs 5a and 6b, what is the significance of the atomic number (often represented by the symbol Z) above each atomic symbol in the periodic table?

8. Based on the answer to CTQ 7, what do all nickel (Ni) atoms have in common?

9. In terms of the numbers of protons, neutrons and electrons:
   a) Why does the notation $^{13}C^{-}$ have a negative sign in the upper right hand corner?

   b) What feature distinguishes a neutral atom from an ion?

   c) Provide an expression for calculating the charge on an ion.

10. a) What are the two isotopes of carbon shown in the model?

    b) Based on the information in the model, what structural feature is different in isotopes of a particular element?

11. The left-hand superscript next to the atomic symbol as shown in the Model is known as the **mass number**, often represented by the symbol A. Surprisingly, the mass number is *not* determined from the mass of the atom.
    a) What is the mass number for the carbon ion in the Model?
    b) Use the information in the completed tables from CTQs 3 and 6a to describe how the mass number is obtained in a grammatically correct sentence.

12. Determine the number of protons, neutrons, and electrons in one $^{1}H^{+}$ ion. Describe the thinking used to determine each value.

13. Show that the mass number and charge given for $^{16}O^{2-}$ and $^{23}Na^{+}$ are correct in the Model.

14. Using information from the Model, where is most of the mass of an atom or ion: within the nucleus or outside of the nucleus? Explain your reasoning using grammatically correct sentences and including specific information from the Model.

Exercises

1. Complete the following table.

Isotope	Atomic Number Z	Mass Number A	Number of Electrons
^{31}P	15		
^{18}O			8
	19	39	18
$^{58}Ni^{2+}$		58	

2. What is the mass (in grams) of :
   a) one ^{1}H atom?
   b) one ^{12}C atom?
3. What is the mass (in grams) of 4.35×10^{6} atoms of ^{12}C?
4. What is the mass (in grams) of 6.022×10^{23} atoms of ^{12}C?
5. What is the mass (in grams) of one molecule of methane which has one ^{12}C atom and four ^{1}H atoms, $^{12}C^{1}H_4$?
6. a) Define mass number.
   b) Define atomic number.
7. Indicate whether the following statement is true or false and explain your reasoning.

   An ^{18}O atom contains the same number of protons, neutrons, and electrons.
8. How many electrons, protons, and neutrons are found in each of the following?

   ^{24}Mg $^{23}Na^{+}$ ^{35}Cl $^{35}Cl^{-}$ $^{56}Fe^{3+}$ ^{15}N $^{16}O^{2-}$ $^{27}Al^{3+}$

9. Complete the following table.

Isotope	Atomic Number Z	Mass Number A	Number of Electrons
	27	59	25
^{14}N			
	3	7	3
	3	6	3
$^{58}Zn^{2+}$			
$^{19}F^{-}$			

10. Using grammatically correct sentences, describe what the isotopes of an element have in common and how they are different.

Problems

1. Estimate the mass of one ^{14}C atom (in amu) as precisely as you can (from the data in the model). Explain your reasoning.
2. Use the data in Model 1 to estimate the values (in amu) of:
   a) the mass of an electron
   b) the mass of a proton
   c) the mass of a neutron
3. The mass values calculated in Problem 2 are only approximate because when atoms (up through iron) are made (mainly in stars) from protons, neutrons, and electrons, energy is released. Einstein's equation $E = mc^2$ enables us to relate the energy released to the mass loss in the formation of atoms. Use the known values for the mass of a proton, 1.0073 amu, the mass of a neutron, 1.0087, and the mass of an electron, 5.486×10^{-4} amu, to show that the mass of a ^{12}C atom is less than the sum of the masses of the constituent particles.

<u>ChemActivity</u> **2**

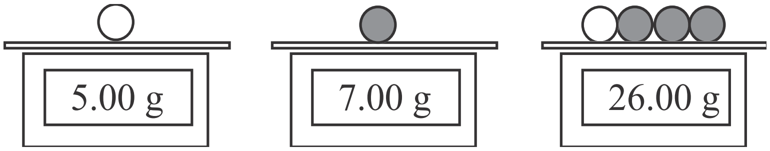
Atomic Number and Atomic Mass

(Are All of an Element's Atoms Identical?)

WARM–UP

Model 1: The Average Mass of a Marble.

In a collection of four marbles, 25% of the marbles have a mass of 5.00 g and 75% of the marbles have a mass of 7.00 g.



The average mass of a marble can be determined by dividing the total mass of the marbles by the total number of marbles:

$$\text{average mass of a marble} = \frac{1 \times 5.00\text{ g} + 3 \times 7.00\text{ g}}{4} = 6.50\text{ g} \qquad (1)$$

Or, the average mass of a marble in this collection can be determined by

i) multiplying the fraction of marbles of a particular type by the mass of a marble of that type; and then

ii) taking a sum over all types of marbles:

$$\text{average mass of a marble} = 0.2500 \times 5.00\text{ g} + 0.7500 \times 7.00\text{ g} = 6.50\text{ g} \qquad (2)$$

Critical Thinking Questions

1. How many of the four marbles in Model 1 have the same mass as the average mass?

2. For a large number of marbles (assume that the actual number of marbles is unknown), 37.2% have a mass of 10.0 g and 62.8% have a mass of 12.00 g. Which of the two methods in Model 1 should be used to determine the average mass of this collection? Explain your answer.

END OF WARM-UP

Model 2: Isotopes.

Each element found in nature occurs as a mixture of isotopes. The relative amount of the isotopes of one element, generally expressed as percentages, is called the **isotopic abundance.** The isotopic abundance can vary substantially on an astronomical scale—in the Sun and on Earth, for example. On Earth, however, the abundance shows little variation from place to place.

Table 1. Isotopic abundance on Earth and atomic masses for isotopes of several elements.

Isotope	Isotopic Abundance on Earth (%)	Atomic Mass (amu)
^{1}H	99.985	1.0078
^{2}H	0.015	2.0140
^{12}C	98.89	12.0000
^{13}C	1.11	13.0034
^{35}Cl	75.77	34.9689
^{37}Cl	24.23	36.9659
^{24}Mg	78.99	23.9850
^{25}Mg	10.00	24.9858
^{26}Mg	11.01	25.9826

1 amu = 1.6606×10^{-24} g

Critical Thinking Questions

3. How many isotopes of magnesium occur naturally on Earth?

4. Describe what all isotopes of magnesium have in common and also how they are different.

5. If you select one carbon atom at random, the mass of that atom is most likely to be __________ amu.

6. What is the mass (in amu) of

   a) 1000 ^{12}C atoms?

   b) 1000 ^{13}C atoms?

7. If you select 1000 carbon atoms at random, the total mass will most likely be:
   - i) 12000.0 amu
   - ii) slightly more than 12000.0 amu
   - iii) slightly less than 12000.0 amu
   - iv) 13003.4 amu
   - v) slightly less than 13003.4 amu

   Explain your reasoning.

8. We would like to calculate the average mass of a Cl atom from the data of Table 1.
   - a) Explain why equation 2 in Model 1 provides a preferred method for calculating the average mass of a Cl atom compared to using equation 1. (Hint: see your answer to CTQ 2.)
   - b) Use the method of equation 2 in Model 1 to calculate the average mass of a chlorine atom in amu.
   - c) What fraction or percentage of chlorine atoms has this average mass?

9. For any large collection of (randomly selected) chlorine atoms:
   - a) What is the average atomic mass of chlorine in amu?
   - b) What is the average mass of a chlorine atom in grams? (Note that the relationship between grams and amu is given in Model 2.) Show your work.

10. Individually, use your answer to CTQ 9b to calculate the mass (in grams) of 6.022×10^{23} (randomly selected) chlorine atoms. Once all group members have completed the calculation, compare your answers and come to consensus.

11. For a large collection of (randomly selected) magnesium atoms:
    a) What is the average atomic mass of magnesium, Mg, in amu?

    b) What is the average mass of a Mg atom in grams? Show your work.

12. Individually, use your answer to CTQ 11b to calculate the mass (in grams) of 6.022×10^{23} (randomly selected) magnesium atoms. Confirm that all group members have the same answer.

13. Complete the following table based on your answers to CTQs 9 – 12.

	Average mass of one atom in amu	Average mass of one atom in grams	Average mass of 6.022×10^{23} atoms in grams
Cl			
Mg			

14. Examine the periodic table and find the symbol for magnesium.

    a) How does the number given just below the symbol for magnesium (rounded to two decimal places) compare with the average mass (in amu) of one magnesium atom?

    b) How does the number given just below the symbol for magnesium (rounded to two decimal places) compare with the mass (in grams) of 6.022×10^{23} magnesium atoms?

15. Find the symbol for chlorine on the periodic table.

    a) How does the number given just below the symbol for chlorine (rounded to two decimal places) compare with the average mass (in amu) of one chlorine atom?

    b) How does the number given just below the symbol for chlorine (rounded to two decimal places) compare with the mass (in grams) of 6.022×10^{23} chlorine atoms?

16. Give two interpretations of the number "12.011" found below the symbol for carbon on the periodic table.

17. What fraction or percentage of carbon atoms has a mass of 12.011 amu?

Model 3: The Mole.

1 dozen items = 12 items

1 mole of items = 6.022×10^{23} items

Critical Thinking Questions

18. a) How many elephants are there in a dozen elephants?
    b) Which has more animals—a dozen elephants or a dozen chickens?
    c) How many elephants are there in a mole of elephants?
    d) Which has more animals—a mole of elephants or a mole of chickens?
    e) Which has more atoms—a dozen H atoms or a dozen Ar atoms?
    f) Which has more atoms—a mole of hydrogen atoms or a mole of argon atoms?

19. Without using a calculator:
    a) Which weighs more, 18 elephants or two dozen elephants? Explain your reasoning.
    b) Which weighs more, 5.136×10^{23} sodium atoms or one mole of sodium atoms? Explain your reasoning.

20. Which has more atoms: 1.008 g of hydrogen or 39.95 g of argon? Explain your reasoning.

Exercises

1. Without doing the calculations, what is the mass in grams of:
   a) 6.022×10^{23} hydrogen atoms (random)?
   b) 6.022×10^{23} potassium atoms (random)?
2. What is the mass in grams of:
   a) 12.044×10^{23} sodium atoms?
   b) 15.0×10^{23} sodium atoms?
3. Define isotope.
4. Describe the difference between ^{35}Cl and ^{37}Cl.
5. Show that equations 1 and 2 in Model 1 are equivalent by showing how the arithmetic expression in equation 1 can be transformed into the arithmetic expression in equation 2.
6. Isotopic abundances are different in other parts of the universe. Suppose that on planet Krypton we find the following stable isotopes and abundances for boron:

^{10}B (10.013 amu)	65.75%
^{11}B (11.009 amu)	25.55%
^{12}B (12.014 amu)	8.70%

   What is the value of the average atomic mass of boron on planet Krypton?
7. Naturally occurring chlorine is composed of ^{35}Cl and ^{37}Cl. The mass of ^{35}Cl is 34.9689 amu and the mass of ^{37}Cl is 36.9659 amu. The average atomic mass of chlorine is 35.453 amu. What are the percentages of ^{35}Cl and ^{37}Cl in naturally occurring chlorine?
8. Without doing any calculations, what is the mass, in grams, of:
   a) one mole of helium atoms?
   b) one mole of potassium atoms?
9. What is the average mass, in grams, of:
   a) one helium atom?
   b) one potassium atom?
10. What is the mass, in grams, of 5.000 moles of carbon atoms?
11. How many sodium atoms are there in 6.000 moles of sodium?
12. How many sodium atoms are there in 100.0 g of sodium?

13. Calculate the number of *atoms* in each of the following:
    a) 50.7 g of hydrogen
    b) 1.00 milligram of cobalt
    c) 1.00 kilogram of sulfur
    d) 1.00 ton of iron
14. Which element contains atoms that have an average mass of 5.14×10^{-23} grams?
15. What mass of iodine contains the same number of atoms as 25.0 grams of chlorine?

Problems

1. Neon has two isotopes with significant natural abundance. One of them, ^{20}Ne, has an atomic mass of 19.9924 amu, and its abundance is 90.5%. Show that the other isotope is ^{22}Ne. Explain your reasoning and include any assumptions that you make.
2. Indicate whether each of the following statements is true or false and explain your reasoning.
    a) On average, one Li atom weighs 6.941 grams.
    b) Every H atom weighs 1.008 amu.
    c) A certain mass of solid Na contains fewer atoms than the same mass of gaseous Ne.
    d) The average atomic mass of an unknown monatomic gas is 0.045 g/mol.
3. The entry in the periodic table for chlorine contains the symbol Cl and two numbers: 17 and 35.453. Give four pieces of information about the element chlorine which can be determined from these numbers (two pieces for each number).
4. The atomic mass of rhenium is 186.2. Given that 37.1% of natural rhenium is rhenium-185, what is the other stable isotope?

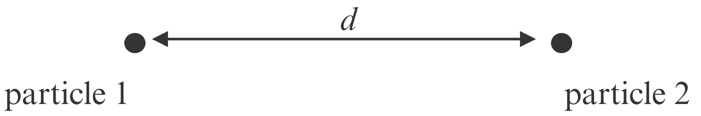
ChemActivity 3

Coulombic Potential Energy

(What Is Attractive About Chemistry?)

WARM–UP

Model 1: Two Charged Particles Separated by a Distance "*d*".



charge on particle 1 = q_1

charge on particle 2 = q_2

$$V = \frac{kq_1q_2}{d}$$

The **potential energy** (V) of two stationary charged particles is given by the equation above, where q_1 and q_2 are the charges on the particles (e.g., –1 for an electron), d is the distance between the particles, and k is a positive-valued proportionality constant. This relationship is known as Coulomb's Law or the Coulombic Potential Energy equation. On the atomic scale, a convenient unit of distance is the picometer, pm. 1 pm = 10^{-12} m.

Critical Thinking Questions

1. Assuming that q_1 and q_2 remain constant, what happens to the magnitude of V if the separation, d, is increased?
2. If the two particles are separated by an infinite distance (that is, $d = \infty$), what is the value of V?
3. If d is finite, and the particles have the same charge (that is, $q_1 = q_2$), is $V > 0$ or is $V < 0$? Explain your answer.

4. If q for an electron is –1,
   a) what is q for a proton?
   b) what is q for a neutron?
   c) what is q for the nucleus of a C atom?

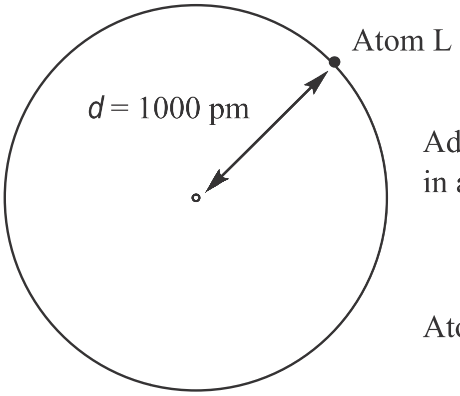
5. Recall that a ^{1}H atom consists of a proton as the nucleus and an electron outside of the nucleus. Is the potential energy, V, of a hydrogen atom a positive or negative number? Explain your answer.

END OF WARM-UP

Model 2: Ionization Energy.

The ionization energy (IE) is the amount of energy needed to remove an electron from an atom and move it infinitely far away. Ionization energies are commonly measured in joules, J.

Figure 1. Ionization of a hypothetical atom L with one proton and one *stationary* electron.

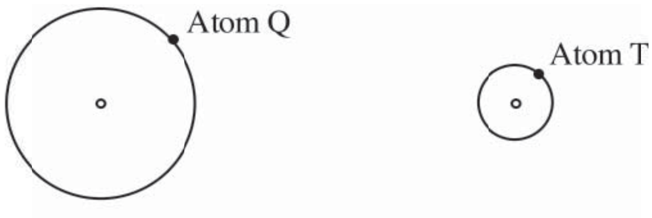


Adding 0.231×10^{-18} J to Atom L results in a bare proton and a free electron.

$$\text{IE} = 0.231 \times 10^{-18}\ \text{J}$$

$$\text{Atom L} + 0.231 \times 10^{-18}\ \text{J} \longrightarrow p^{+} + e^{-}$$

Figure 2. Ionization energies of two hypothetical atoms, each with one proton and one *stationary* electron separated by distance "*d*".



d = 500 pm
IE = 0.462×10^{-18} J

d = 200 pm
IE = 1.16×10^{-18} J

Table 1. Ionization energies of several hypothetical atoms, each with one proton and one *stationary* electron separated by distance "*d*".

Hypothetical Atom	d (pm)	IE (10^{-18} J)	V (10^{-18} J)
A	∞	0	
E	5000.	0.0462	
L	1000.	0.231	
Q	500.0	0.462	
T	200.0	1.16	
Z	100.0	2.31	

Critical Thinking Questions

6. Based on the data in Table 1, which of these is the correct value for the ionization energy of atom E?

   i) 0.0462 J
   ii) 4.62×10^{-16} J
   iii) 4.62×10^{-18} J
   iv) 4.62×10^{-20} J
   v) 4.62×10^{16} J

7. A student determines the ionization energy of another hypothetical atom and gets 5.13×10^{-17} J. If this hypothetical atom were added to Table 1, which of the following values would be entered in the IE column?

   i) -5.13
   ii) 5.13
   iii) 51.3
   iv) 0.513

8. Do you expect the potential energy, V, of the hypothetical atoms in Table 1 to be positive or negative numbers? Explain your reasoning.

9. Without using a calculator, predict what trend (if any) you expect for the values of V for these hypothetical atoms.

10. Calculate the potential energy, V, for each of the hypothetical atoms to complete Table 1. Use the value $k = 2.31 \times 10^{-16}$ J·pm.

11. Based on the results in Table 1, provide a mathematical expression that describes the relationship between IE and V for these hypothetical atoms.

For each of the remaining CTQs, each team member should arrive at an answer individually. Then the team should discuss the answers and reach consensus. Be sure to write the consensus explanation from your team.

12. Which of the following systems will have the larger ionization energy? Explain your reasoning.
    i) an electron at a distance of 500 pm from a nucleus with charge +2
    ii) an electron at a distance of 700 pm from a nucleus with charge +2

13. Which of the following systems will have the larger ionization energy? Explain your reasoning.
    i) an electron at a distance d_1 from a nucleus with charge +2
    ii) an electron at a distance d_1 from a nucleus with charge +1

14. How many times larger is the larger of the two ionization energies from CTQ 13? Show your work.

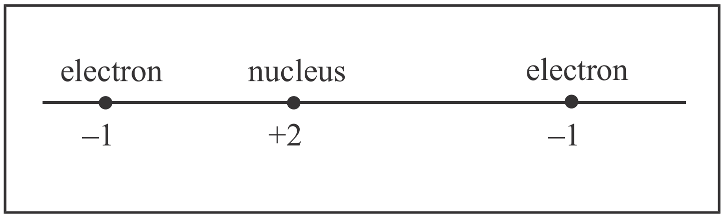
15. Consider a hydrogen atom and a helium ion, He^+. Which of these do you expect to have the larger ionization energy? Explain your reasoning, including any assumptions you make.

Exercises

1. For a hypothetical atom (as in Table 1) with $V = -5.47 \times 10^{-18}$ J, what would the IE be?
2. Which of the following systems will have the larger ionization energy? Show your work.
    i) an electron at a distance d_1 from a nucleus with charge +2
    ii) an electron at a distance $2d_1$ from a nucleus with charge +1
3. Which of the following systems has the larger ionization energy?
    i) an electron at a distance $5d_1$ from a nucleus with a charge of +6
    ii) an electron at a distance $6d_1$ from a nucleus with a charge of +7

Problems

1. According to the Coulombic Potential Energy equation, if a particle with a charge of –1 is *extremely* close to a particle with a charge of +2, the potential energy is:
    i) large and positive
    ii) large and negative
    iii) small and negative
    iv) small and positive
2. Two electrons and one helium nucleus are arranged in a straight line as shown below. The electron on the left is 300 nm from the nucleus; the electron on the right is 400 nm from the nucleus. Write the *three* Coulombic Potential Energy terms for this arrangement of charges.



ChemActivity 4

The Shell Model (I)

(How Are Electrons Arranged?)

WARM–UP

Electrons in atoms are attracted to the nucleus by a Coulombic force. As shown in CA 3, energy must be supplied (by some means) to pull an electron away from the nucleus, thereby creating a positively charged species, or **cation**, and a free electron. For real atoms, which may contain more than one electron, the minimum energy required to remove an electron from a gaseous atom of that element is called the **first ionization energy** (IE_1) of that element.

Ionization energies are usually obtained experimentally. One method of measuring ionization energies is the electron impact method. Atoms of a given element are bombarded with fast-moving electrons from another source. If these fast-moving electrons have sufficient energy, they will, on colliding with an atom, eject one of the atom's electrons. The first ionization energy corresponds to the smallest amount of energy that a bombarding electron needs to be able to knock off one of the atom's electrons.

Model 1: First Ionization Energy (IE_1).

$$M(g) \longrightarrow M^+(g) + e^-$$

For a H atom, IE = 2.178×10^{-18} J.

The first ionization energy, IE_1, for a single atom is a very small number of joules. For reasons of convenience, chemists report the ionization energies of elements in terms of the minimum energy necessary to remove a single electron from each atom in a mole of atoms of a given element. This results in ionization energies for the elements that are in the range of MJ/mole. (Note that 1 MJ = 10^6 J.)

Critical Thinking Questions

1. a) How much energy does it take to remove an electron from one H atom?

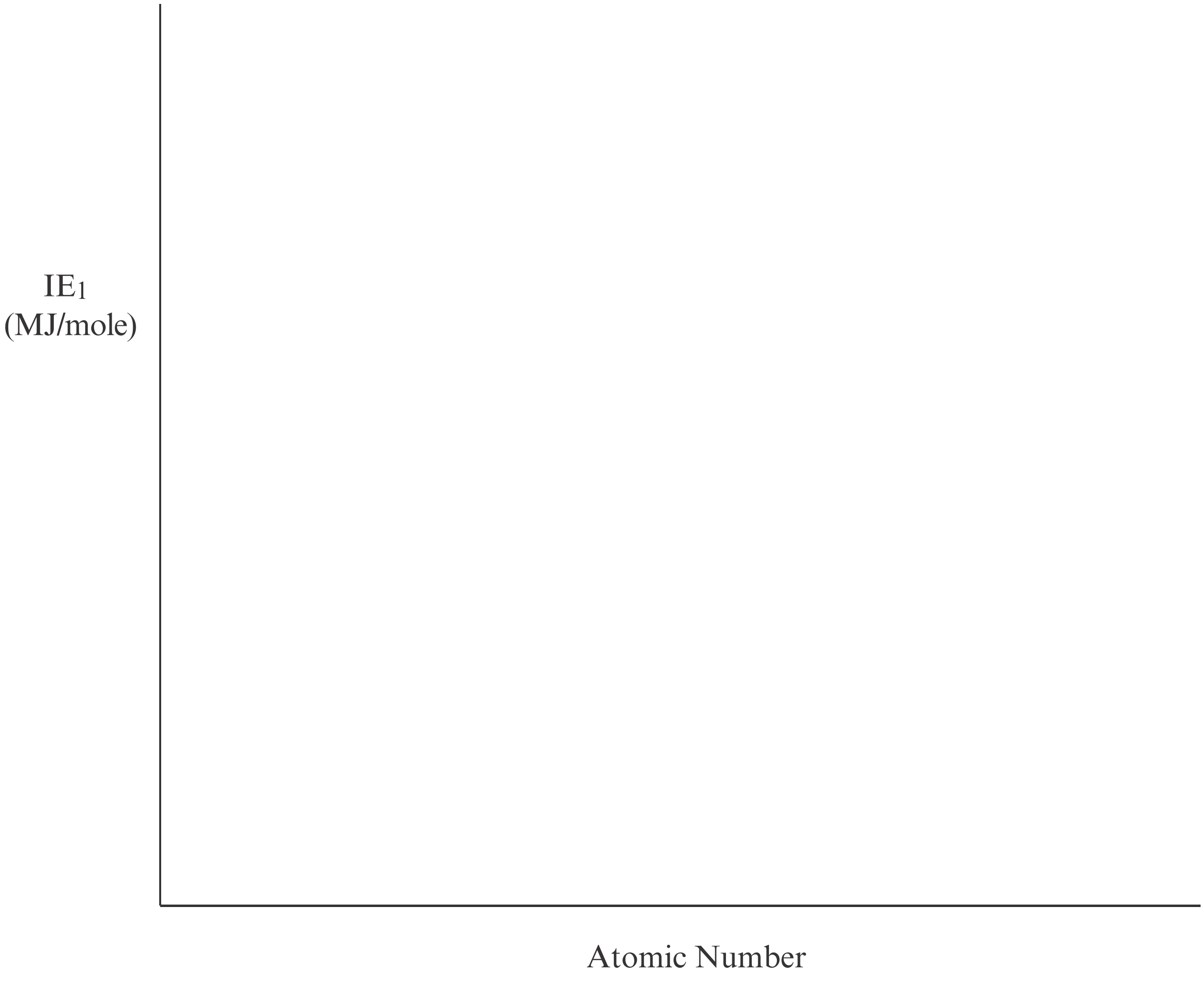
   b) How much total energy would it take to remove the electrons from two H atoms?

   c) How much total energy would it take to remove the electrons from a mole of H atoms? Express this energy in units of J and in units of MJ.

END OF WARM–UP

2. For atoms with many electrons, not all electrons are at the same distance from the nucleus. In this case, which electron would have the lowest ionization energy: the electron that is closest to the nucleus or the electron that is farthest from the nucleus? Explain.

3. Based on what you have learned so far in this course, predict the relationship between IE_1 and atomic number by making a rough graph of IE_1 vs. atomic number. Discuss possible ideas with your team and decide which one you think makes the most sense. DO NOT PROCEED TO THE NEXT PAGE UNTIL YOU HAVE MADE YOUR PREDICTED GRAPH.



Information

Based on our previous examination of ionization energies, it is expected that the first ionization energy of an atom (often referred to as simply the **ionization energy**) would increase as the nuclear charge, Z, increases. In addition, the ionization energy of an atom should decrease if the electron being removed is moved farther from the nucleus (that is, if *d* increases).

Table 1 below presents the experimentally measured ionization energies of the first 20 elements. We will examine these results and attempt to propose a model for the structure of atoms based on these data.

Table 1. First Ionization energies of the first 20 elements.

Z		IE_1 (MJ/mole)	Z		IE_1 (MJ/mole)
1	H	1.31	11	Na	0.50
2	He	2.37	12	Mg	0.74
3	Li	0.52	13	Al	0.58
4	Be	0.90	14	Si	0.79
5	B	0.80	15	P	1.01
6	C	1.09	16	S	1.00
7	N	1.40	17	Cl	1.25
8	O	1.31	18	Ar	1.52
9	F	1.68	19	K	0.42
10	Ne	2.08	20	Ca	0.59

Critical Thinking Questions

4. Compare your answer to CTQ 3 to the data in Table 1. Comment on any similarities and differences.

5. Using grammatically correct sentences:
   a) provide a possible explanation for why IE_1 for He is greater than IE_1 for H.

   b) provide a possible explanation for why IE_1 for Li is less than IE_1 for He.

Model 2: Simple Model Diagrams for Hydrogen and Helium Atoms.

One simple model of the hydrogen atom pictures the H atom as a nucleus of charge +1 surrounded by an electron at some distance, as shown in Figure 1.

Figure 1. Model diagram of a hydrogen atom.

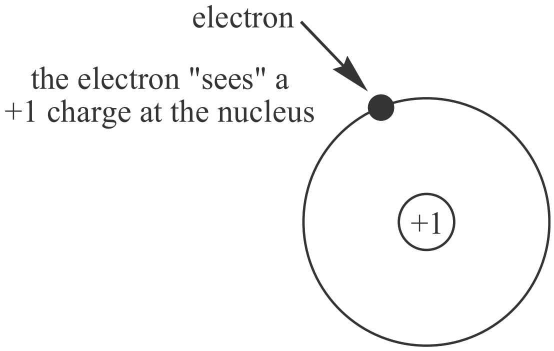
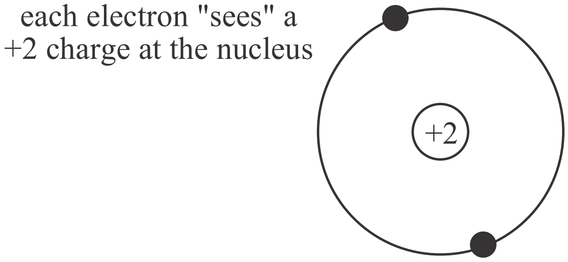


Figure 2. Model diagram of a helium atom.



Examining the data in Table 1, we note that the ionization energy of He (Z = 2) is larger than that of H (Z = 1) by approximately a factor of 2. This is consistent with a model in which the two electrons in the He atom are at a distance (from the nucleus) approximately the same as that in H.

Critical Thinking Question

6. The value of the ionization energy of He given in Table 1 is described as being consistent with a model in which the two electrons in He are in a "shell" at approximately the same distance from the nucleus as the one electron in H.

   Use the Coulombic Potential Energy equation, $V = \frac{kq_1q_2}{d}$ to explain how this conclusion can be reached. Hint: recall the relationship between V and IE_1.

Information

Because the He nucleus has a charge of +2, we would expect that the ionization energy to remove an electron from (approximately) the same distance as in a H atom would be (approximately) twice that of the H atom. That is what we observe. We can say that there are two electrons in a **shell** around the He nucleus. Although we will present figures in which the shells appear to be circular (mostly because it is difficult to present three-dimensional representations on paper), we recognize that the model we develop is qualitatively consistent with spherical shells. Thus, within our *Shell Model*, He consists of a nucleus surrounded by 2 electrons in a single shell.

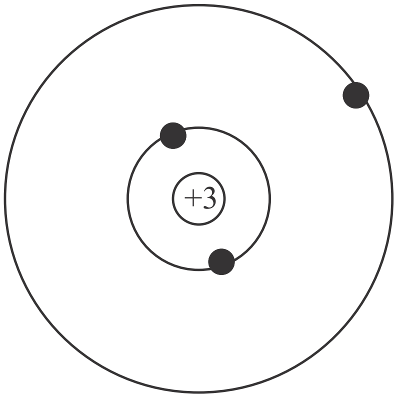
Critical Thinking Questions

7. Recall that the IE of H is 1.31 MJ/mole. If all three electrons in Li were in the first shell at a distance equal to that of hydrogen, which of the following values would be the better estimate of the IE_1 of Li: 3.6 MJ/mole or 0.6 MJ/mole? Explain your reasoning.

8. A student proposes a model for the Li atom in which all three electrons are in the first shell at a distance approximately the same as in H. Why is this model *not consistent* with the IE_1 for Li in Table 1?

9. Another student proposes a model for the Li atom in which two electrons are in the first shell (as in He) and the third electron is much farther from the Li nucleus, as shown in Figure 3. Explain how this model *is consistent* with the IE_1 for Li in Table 1.

Figure 3. Diagram of a lithium atom based on student proposal in CTQ 9.



10. Based on the model of a Li atom shown in Figure 3, would the amount of energy required to remove one of the electrons from the first shell of Li be greater than, less than, or equal to the IE_1 for Li? Explain your reasoning.

Exercises

1. A scientist proposes a model for the helium atom in which both electrons are in a "shell" which is half the distance from the nucleus as the electron in a hydrogen atom. Is this model consistent with the data in Table 1? Explain your reasoning. (Hint: according to the Coulombic Potential Energy equation, how much more strongly does a nuclear charge of +2, as in He, hold an electron than a nuclear charge of +1, as in H? According to the Coulombic Potential Energy equation, how much more strongly does a nuclear charge hold an electron if it is at $d/2$, rather than d?)
2. Propose an alternative model for the lithium atom that is consistent with the data in Table 1.

Problem

1. a) Write the three Coulombic Potential Energy terms for the helium atom model in Figure 2. Assume that the distance between each electron and the nucleus is d and that the distance between the two electrons is $2d$.

   b) Based on your answer to part a, explain why the IE_1 of He is slightly less than twice the IE_1 of H even though both atoms are about the same size.

ChemActivity 5

The Shell Model (II)

WARM-UP

Information: The Shell Model for Li.

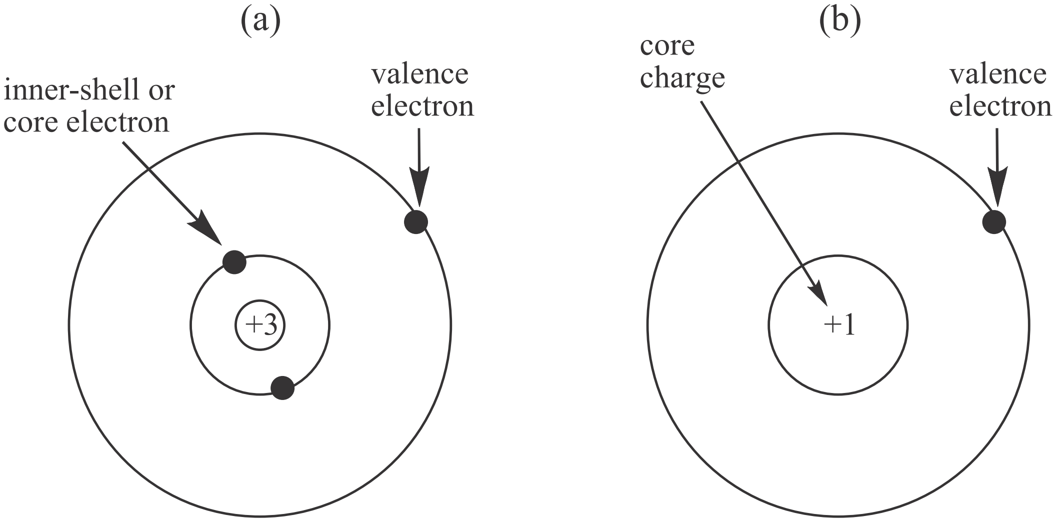
For Li, there is a change in the trend of the ionization energy compared to H and He. The ionization energy of a Li atom is *less* than that of He. In fact, it is significantly *smaller* than that of the H atom! This is not consistent with a model of placing a third electron in the first shell, for doing so would result in an ionization energy that is larger than that of He. In order for Li to have a lower ionization energy than H, either the nuclear charge Z for Li must be lower than that of H, or the distance of the easiest-to-remove electron from the nucleus must be greater than in H (and He), or both. We know that the nuclear charge of Li is *not* lower than that of H; thus, the easiest-to-remove electron must be farther from the nucleus than the first shell in H. Although the data we have does not require us to choose the following model, let us assume that the structure of Li involves two electrons in a first shell (as in He) with the third electron placed in a second shell, with a significantly larger radius, as shown in Figure 1a on the next page.

Model 1: Valence Electrons, Inner-Shell Electrons, Core Charge, and Electron-Electron Repulsion.

The electrons in the outermost shell of an atom are referred to as **valence** electrons. Electrons in any other shells closer to the nucleus are called **inner-shell** electrons. Thus, Li has one valence electron and two inner-shell electrons. H has one valence electron and no inner-shell electrons.

The nucleus plus the inner shells of electrons constitute the **core** of the atom, and the net overall charge on the core is called the **core charge**. We can represent the Li atom in terms of core charge as shown in Figure 1b.

Figure 1. Diagram of a lithium atom using (a) the shell model and (b) the core charge concept.



Notice that within the shell model of the Li atom, shown in Figure 1a, the valence electron is farther from the nucleus than the two inner-shell electrons. Although we have ignored it up to this point, we should remember that all of the electrons repel each other because they are negatively charged. Of particular interest is the repulsion of the valence electron by the two inner-shell electrons. This dramatically decreases the overall force of attraction pulling the valence electron toward the nucleus.

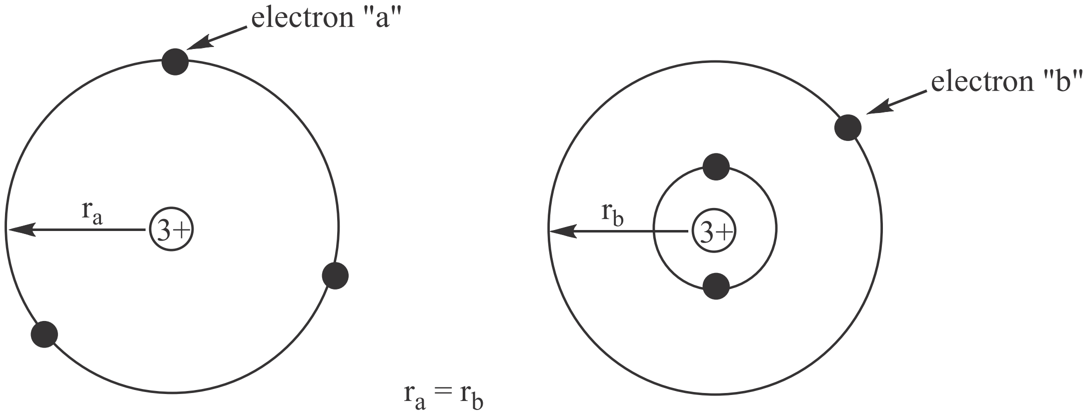
Thus, the outer-shell valence electrons experience the charge of the core rather than the full charge of the nucleus. The core electrons that surround the nucleus are said to *shield* the nucleus from the valence electrons. In fact, because the valence electrons are all negatively charged, they repel each other also. Thus the net resulting charge acting on a valence electron to attract it toward the nucleus differs from the core charge. This overall resulting charge acting on a valence shell electron is known as the **effective nuclear charge**, and it is generally less than the core charge. Since there is no simple way to obtain values for the effective nuclear charge, we will use the core charge as a basis for our qualitative explanations. Core charge is only an approximation for effective nuclear charge, but it is adequate for our purposes.

Critical Thinking Questions

1. Complete the following table:

Atom	Total number of electrons	Number of valence shell electrons	Number of inner shell electrons	Core Charge
H	1			
He				
Li				+1

2. Two possible models for arrangement of electrons in Li are shown below:



Explain why the IE_1 of electron “b” would be less than the IE_1 of electron “a”.

END OF WARM-UP