Bonding in Ionic, Covalent, and Cluster Solids

Purpose

This lesson serves as a review of ionic and covalent bonding and macroscopic properties of ionic and covalent solids. It also introduces students to a novel class of materials, cluster solids, which contain bonds with ionic and covalent properties.

Audience

This lesson was designed to be used in an introductory high school chemistry course.

Lesson Objectives

Upon completion of this lesson, students will be able to:

- compare particulate structures and macroscopic properties of three types of solids—ionic, covalent, and cluster solids (a novel type of solid developed recently).
- explain how the particulate structure of each type of solid determines its macroscopic properties, including conductivity and solubility.

Key Words

cluster solids, cluster units, electrical conductors, fullerene (C_{60}), ionic solids, metallic solids, molecular solids, valence electrons

Big Question

This lesson addresses the Big Question, *"What does it mean to observe?"*

Standard Alignments

- **Science and Engineering Practices**
  - **SP 2.** Developing and using models
  - **SP 6**. Constructing explanations
- **MA Science and Technology/Engineering Standards (2016)**

  HS-PS1-3. Cite evidence to relate physical properties of substances at the bulk scale to spatial arrangements, movement, and strength of electrostatic forces among ions, small molecules, or regions of large molecules in the substances. Make arguments to account for how compositional and structural differences in molecules result in different types of intermolecular or intramolecular interactions.

- **NGSS Standards (2013)**

  HS-PS1-3. Plan and conduct an investigation to gather evidence to compare the structure of substances at the bulk scale to infer the strength of electrical forces between particles.

- **Common Core Math/Language Arts Standards**
  - **CCSS.ELA-LITERACY.RST.9-10.1**. Cite specific textual evidence to support analysis of science and technical texts, attending to the precise details of explanations or descriptions.
  - **CCSS.ELA-LITERACY.RST.11-12.2**. Determine the central ideas or conclusions of a text; summarize complex concepts, processes, or information presented in a text by paraphrasing them in simpler but still accurate terms.

Misconceptions Addressed

- This lesson addresses many common misconceptions about bonding and bonding representations, including:
  - Ionic compounds share electrons (Question 6)
  - Covalent compounds have a transfer of electrons (Question 7)
- Further information about student misconceptions on this topic can be found here.

Primary Sources

- **Bite** "Cluster Solids: Ionic, Covalent or Both?" *based on*:

  Roy, Xavier Roy, Chul-Ho Lee, Andrew C. Crowther, Christine L. Schenck, Tiglet Besara, Roger A. Lalancette, Theo Siegrist, Peter W. Stephens, Louis E. Brus, Philip Kim, Michael L. Steigerwald, and Colin Nuckolls. 20123 "Nanoscale Atoms in Solid-State Chemistry," *Science* 34: 157-160. doi: 10.1126/science.1236259

- **Misconceptions**

  Luxford, Cynthia J. and Stacey Lowery Bretz. 2014. "Development of the Bonding Representations Inventory To Identify Student MIsconceptions about Covalent and Ionic Bonding Representations." Journal of Chemical Education 91: 312–320. doi: 10.1021/ed400700q

Materials

- Six 2-inch round colored stickers, Eight ⅜ inch round colored stickers, Six ¾ inch round white stickers, and a copy of Models of Solids template for each pair of students
- Copies of the Student Handout and Science Bite for each student

Time

This activity should take approximately one 50-minute class period.

Student Prior Knowledge

Students should be familiar with the basic structure of ionic and covalent bonds and properties of ionic and covalent solids.

Instructions and Teacher Tips

- **General Procedure**
  - In pairs, have students create models of solid types with stickers (explained in detail in the Teacher Tips section below). After creating models, students will compare and contrast the models and then make predictions about properties of the three types of substances.
  - Have a whole class discussion around the similarities and differences in the models and students' predictions.
  - Students will then read the Bite and answer analysis questions.
  - To wrap-up, the whole class discusses structure-property relationships in the three types of solids and applications of cluster solids. The wrap-up should take about 10 minutes.
- **Teacher Tips**
  - Stickers are used as physical representations of individual units (molecules, ions and clusters) of different types of solids (molecular, ionic and cluster, respectively).
    - Colored stickers represent charged units (cations and anions), while white stickers represent neutral units (molecules)
    - The different sticker sizes demonstrate the relative sizes of the units in each of the three types of solids.
  - These stickers are inexpensive and readily available on Amazon. It is also easy to do the lesson without stickers. Students color in the cations and anions different colors to show the alternating array of charged particles visually.
  - Students should select (or you can select for them) two different colors of stickers for their cations and anions. They should use the same color for cations in the ionic and cluster models and the same color for anions in both models to emphasize the similar alternating array of cations and anions found in both types of solids.

Big Question Discussion

This lesson should get students thinking about the Big Question "*What does it mean to observe?*" In particular, it explores how understanding chemistry means understanding the particulate nature of matter, which is on such a tiny scale it is difficult to observe. If you choose to delve into the Big Question, consider the following ideas:

- A discussion of the experimental ingenuity required to characterize the particles in this study will help students to appreciate the universality of the Big Question to chemistry. The researchers used x-ray diffraction patterns to infer the structure of both the cluster units and the cluster solids by looking at how light was scattered by the materials. The experiment is carried out by mixing the materials together and letting them crystallize out of solution, similar to how you can make rock candy using a solution of sugar water. It's hard to predict the exact way the transition metal cluster units will combine with C_{60}, so this complicates analyzing the x-ray structure because it's not being compared to a hypothesis or intended structure.

- Another point to highlight with students could be the nature of models. The structures had to be recreated using computer modeling based on the diffraction of light. The students could discuss what are the pros and cons of using computer models. On the one hand, computers are much more powerful than our brains are when it comes to computing and calculating. On the other hand, we have to rely on a program, rather than our own senses.

Background Information and Research Details

- This research is part of a larger project to develop a library of "nanoscale atoms." Scientists are trying to develop cluster units (nanoscale compounds that have many atoms making it up) that behave "like atoms" when mixed together in a reaction. Here, "like atoms" means that when two different types of clusters are mixed together, they bond with each other in a manner similar to ionic bonds, by transferring electrons to each other. This is pretty astounding, because they are on a size scale an order of magnitude bigger than atoms that traditionally compose ionic bonds.
- They are developing different cluster units that have transition metal (e.g. Ni, Cr, Co)-chalcogenide (e.g. Se, Te) cores and mixing them with clusters that can be reduced, like C_{60}, to see how they react. The hope is to develop a library of materials that behave like atoms by forming pseudo-ionic bonds. The transition metal complexes transfer electrons to the C_{60} to give it a negative charge, thus behaving like a cation in an ionic bond. The transition metals are capable of carrying a formal positive charge.
- In this activity, students look at two of the cluster units: C_{60}, a soccer-ball shaped structure of 60 carbon atoms bonded together, and a cluster unit made from transition metals in the core of the structure and ligands around it. The transition metal cluster unit is made from nickel, cobalt or chromium cores. The three types of transition metal cluster units have slightly different properties and form different solid state materials when combined with C_{60}. It's not necessary to go into detail about the specific differences between the three types of cluster units, though it might be useful to make the analogy to students that, like sodium and calcium, different cluster units might form different ratios in their bonds. It's hard to predict what the structures will be like based just on the composition of the cluster units because they are so complex, so instead it could be useful to make observations and have the students speculate in an open-ended way what the similarities are between these "nanoscale" atoms and atoms from the periodic table.
    - In this lesson, the students are taught that the cluster solids are not water soluble—most solid state materials are not water soluble. However, these materials are actually not stable in water (or air).

Answers

1. The table below contains the chemical formula of an ionic solid, a covalent solid and a cluster solid. Use your models and the information in Table 1 and the introduction to match each formula with the type of solid (molecular, ionic, or cluster) it represents, and explain how the chemical formula can help you identify the type of solid.

Chemical Formula	Solid Type	Explanation
NaCl	Ionic	Contains two different ions—one positively charged, one negatively charged.
$C_{10}H_8$	Covalent	Contains nonmetal elements only.
$[Ni_9Te_6(PEt_3)_8][C_{60}]$	Cluster	Contains very large particles.

2. Examining the models you made, compare the ionic solid model to the cluster solid model. What do they have in common? How are they different?

Similarities	Differences
• Contain positively and negatively charged particles • Positive and negative particles are arranged in an alternating array.	• Size of particles is different

3. Rank the size of the particles in each solid from smallest units to largest units.

Model 2 < Model 3 < Model 1 (Ionic < Molecular < Cluster)

4. Use a ruler to measure the diameter of one particle (in cm) of each type of solid model.

Solid Type	Diameter of One Particle in Model (cm)
Cluster	5.10 cm
Ionic	0.95 cm
Molecular	1.90 cm

   a. Approximately how many times larger is the diameter of the cluster solid particle model than the ionic solid particle model?

The largest unit has a diameter about 5 times larger than the smallest.

b. How do the diameters of the particles in the molecular solid model and ionic solid model compare?

The molecular solid unit has a diameter twice as large as the ionic solid.

STOP & read Science Bite: Cluster Solids: Ionic, Covalent, or Both?

5. According to the Bite, cluster solids are held together by electrostatic attractions, just like ionic solids. Why, then, are they not simply classified as ionic solids? Cite evidence from the Bite in your answer.

In addition to the transfer of electrons and the subsequent electrostatic attractions that hold cluster solids together, cluster solids also contain clusters that may be held together by ionic bonds or covalent bonds. Also, as stated in the Bite, there are layers of cluster units that are held together by non-ionic intermolecular forces. Ionic solids only involve bonds that form from electron transfer. Because cluster solids involve other types of bonds, they cannot be simply classified as ionic solids.

6. The Bite also states that cluster solids contain covalently bonded atoms. Why can't cluster solids be considered molecular solids?

Cluster solids include bonds formed from the transfer of electrons. Intramolecular bonds in molecular solids are only formed from the sharing of electrons, so if there are bonds from the transfer of electrons, it cannot be a molecular solid.

7. Generally speaking, ionic compounds dissolve in water and molecular compounds do not. Based on this information do you think cluster solids will dissolve in water? Make a claim and justify your claim with evidence from your models and the Bite.

No, they will not dissolve in water as the particle size is very large and the particles are held together by covalent bonds which are not soluble in water.

8. Which type of solid (ionic, covalent, or cluster) is more likely to be useful in an application requiring electrical conductivity? Explain your answer based on evidence from the Bite.

Cluster solids are more likely to be useful in an application requiring electrical conductivity, because they are specifically designed to have tunable electric properties. Additionally, ionic solids will only conduct electricity if they are dissolved and covalent solids do not conduct electricity.

9. Does the cluster solid model you created (Model 1) show the ionic and covalent features equally or does it emphasize one or the other? Explain your thinking.

The cluster solid model we created emphasizes the ionic components, because it shows how the positively and negatively charged particles form a crystal structure like ionic solids. It shows the cluster units as large monatomic charged species rather than showing the molecular substructure of each of the large charged particles. It is not immediately obvious that within the charged particles there may be covalent bonds.

10. How could Model 1 be improved to more accurately reflect both kinds of bonding present in cluster solids?

Model 1 could be improved to more accurately show the covalent nature of some of the cluster units by including a simplified molecular structure drawing or a chemical formula for the particle within each circle in addition to the charge.

11. Connect to the Big Question. Scientists determined the structures of the cluster solids described in this lesson using x-ray images combined with computer modelling, rather than using their senses, as one typically would do when studying a system in a high school chemistry laboratory. How is the scientists' process similar to and different from more typical modes of observation in chemistry?

Sample answer: In the laboratory observations and measurements are taken using the senses (particularly sight). Direct observation and measurement of cluster solids' structure was not possible so other tools had to be used to provide information that could then be used to describe the structure. Both laboratory observation and the methods used to observe the cluster solids require attention to detail and precision in order to lead to accurate representations of materials and phenomena.