Andrews University
PHYSICS ENTERPRISES

# Mole Cube Set

## Experiment Guide

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Designed by

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# Introduction

## Description

This set contains four element samples: aluminum, iron, copper, and zinc. Each sample has been sized to contain one mole of the element, or $6.022 \times 10^{23}$ atoms. This number is called "Avogadro’s number". If you look up an element's atomic mass and measure out that many grams of the substance, you will have $6.022 \times 10^{23}$ atoms, or one mole, of the element. The samples in this set make it easy to visualize a mole and allow students to practice physical measurements and mole calculations.

The following experiment uses the concept of a mole to identify the elements and estimate their atomic radii. The experiment is concluded with an application of specific heat for element identification.

In addition to mole related experiments and demonstrations, there are a variety of other uses for this set, including density measurements, specific heat experiments, and examples of common elements.

## Safety

Please teach and expect safe behavior in your classroom and lab. Safety considerations call for supervision of students at all times: safety eyewear, no horseplay, immediate reporting to the instructor of accidents or breakage, among others.

This set contains small objects and thus is not suitable for use with young children. This product is not a toy. It is for educational and laboratory use only. It is not intended for use by students age 12 years and under without competent adult supervision.

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# Experiment

## Introduction

In this lab experiment, you will observe and measure samples of metal containing one mole ($6.022 \times 10^{23}$ atoms) of some element. After measuring their physical properties, you will identify the element for each sample and calculate its atomic radius.

## Equipment

- 4 labeled cubes of metal (1 mole each)
- 1 Metric ruler or calipers
- 1 Metric scale or balance
- 1 Scientific calculator (preferred) or standard calculator (will need to calculate in scientific notation)

## Procedure

1. Examine the four samples and record your observations. You are not expected to make any measurements yet.

| Sample | Observations |
|---|---|
| A | |
| B | |
| C | |
| D | |

2. Different kinds of atoms have different masses. How can you tell that this is true from your observations? Did you need to use the fact that each sample contains 1 mole of atoms? Which of the four samples is made of atoms with the least mass?

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3. Since each sample contains the same number of atoms, simple observation will suggest that atoms of different elements have different sizes. List the four samples according to the size of their atoms. State any assumptions you made. Are there any samples whose atoms seem to be the same size?

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4. Sample B is noticeably less dense than the other samples in this set. In terms of the atoms the samples are made of, what are two reasons that Sample B is the least dense? State any assumptions you made.

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5. Use metric measurement tools and a textbook or other references to determine the identity of the four elements in this set. Even if you believe you can identify the elements by sight, you should support your conclusions with numerical data and reasoning from the fact that each sample contains 1 mole of some element. Show and explain your work in the space below. Record your answers in the table.

| **Sample** | **Element Name** |
|---|---|
| A | |
| B | |
| C | |
| D | |

**Before continuing, check that you correctly identified the 4 elements. Ask your instructor if you are unsure.**

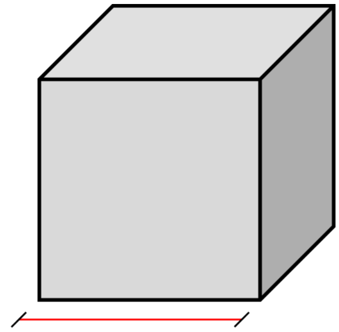
6. Calculate the mass of an atom for each element in this set. Show your calculations in the space below and record your answers in the table. (It is best to perform these calculations in scientific notation.)

| Sample | Element | Mass of Atom (g) |
|---|---|---|
| A | | |
| B | | |
| C | | |
| D | | |

7. Calculate the volume of an atom for each element in this set. In order to answer this question, it is acceptable (and necessary) to make a simplifying assumption about the shape of an atom. Although atoms are complex in shape, it is common to assume they are spherical. For this problem, assume the atoms are cube-shaped. This may seem silly, but it will make your reasoning and calculations easier, while still providing a decent approximation of the atom's volume. Show your calculations in the space below, and record your answers in the table. Express your answers in cubic centimeters.

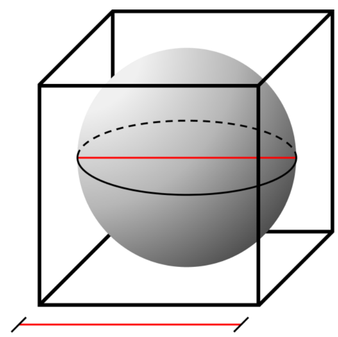
| Sample | Element | Volume of Atom ($cm^3$) |
|---|---|---|
| A | | |
| B | | |
| C | | |
| D | | |

8. Find the edge length of a cube-shaped atom for each element in this set. Remember that the volume of a cube is the edge length cubed (length raised to the power of 3), and likewise the edge length is the cube-root of the volume (or volume raised to the 1/3 power). Show your calculations in the space below, and record your answers in the table. Express your answers in picometers.



| Sample | Element | Edge Length (pm) |
|---|---|---|
| A | | |
| B | | |
| C | | |
| D | | |

9. Chemists often assume that atoms are spherical, and speak of "atomic radius". If we assume the atoms are spheres instead of cubes and that the spheres are packed together in a cubic arrangement (layers of rows and columns), the diameter of the atom will be identical to the edge length of the cube-shaped atom (question 8). Find the atomic <u>radius</u> for each element in this set and compare your results to the values in the provided reference table. If there are discrepancies between your results and the accepted values, speculate on the cause(s) of these differences.



| Sample | Element | Calculated Atomic Radius (pm) | Accepted Atomic Radius (pm) |
|---|---|---|---|
| A | | | |
| B | | | |
| C | | | |
| D | | | |

10. Using these samples for specific heat and heat capacity experiments produces a surprising yet highly instructive result. Find the specific heat and molar heat capacity for each of the four samples. This may be done experimentally in the lab, or by searching published data. Show your calculations in the space below, and record your answers in the table.

| Sample | Element | Specific Heat (J/g°C) | Molar Heat Capacity (J/mol°C) |
|---|---|---|---|
| A | | | |
| B | | | |
| C | | | |
| D | | | |

Note: Specific heat is the energy required to raise the temperature of 1 gram of a substance by 1°C. Heat capacity is the energy required to raise the temperature of the entire object by 1°C (heat capacity = specific heat x mass of object). Molar heat capacity is the energy required to raise the temperature of 1 mole of a substance by 1°C (molar heat capacity = specific heat x molar mass).

11. In the past, analysis of experiments like question 10 provided a method of determining relative atomic masses, at a time before there was universal agreement among scientists of the existence of atoms! This discovery was made by the scientists Petit and Dulong. Suppose you have a sample of an unidentified element. Can you suggest a way to determine its atomic mass and identify it?

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# Answer Key

## Typical Results & Answers

1. Sample Observations:

| Sample | Observations |
|---|---|
| A | Metallic, with grey tarnish of varying darkness. Second largest sample. |
| B | Metallic, silver colored. Obviously less massive, larger, and therefore less dense than the other samples. |
| C | Metallic, dull silver color. Brown deposits on the surface may be possible. One of the two smallest samples. |
| D | Metallic, reddish brown color, like that of a penny. One of the two smallest samples. |

2. Some of the samples obviously have different masses. This could be explained by atoms of equal masses, but unequal number. However, since we know that each sample has the same number of atoms, it must be that the atoms of the heavier specimens have greater mass. Sample B has the least mass.

3. Listing the samples from smallest to largest volume, the order should be C, D, A, B. Given that each sample contains the same number of atoms, logically the volume of each atom must follow the same pattern.

   This assumes the atoms in each sample are arranged in the same internal structure, or at least in structures of the same compactness.*

   Also, note that samples C and D are almost identical in size. Sample C should be slightly smaller than sample D, but their sizes are close enough that variability in manufacturing may cause their order to be reversed.

4. Sample B is the least dense of the four, because its atoms have the least mass and the greatest volume.

   This assumes the atoms in each sample are arranged in the same internal structure, or at least in structures of the same compactness.*

*This assumption is true for samples B, C, and D, but sample A has a different internal structure. Even though the assumption is flawed, the conclusions are correct (for these samples). At the middle school or high school level, it may be appropriate to overlook this detail, but at the college level, the instructor should discuss how different crystal structures determine the density and volume of materials.

5. There are two methods students may use to identify the elements.

   The preferred method is to measure the mass of each sample (in grams), and use the fact that each sample is one mole. By comparing the measured mass of a one mole sample to a table of atomic masses (in grams per mole), students will be able to identify the element that each sample is composed of.

   Alternatively, students may determine the density of each sample (from mass and volume) and compare these measured densities with a table of densities for various metals. This method does not use the mole concept, and is likely to be difficult or impossible to implement. Many metals have similar densities, and the measurement errors may be greater than the differences between published density values.

   Sample measurements, published values, and elements identified:

| Sample | Measured Mass (g/mol) | Atomic Mass (g/mol) | Element Name |
|---|---|---|---|
| A | 65.7 g/mol | 65.38 g/mol | Zinc (Zn) |
| B | 27.3 g/mol | 26.98 g/mol | Aluminum (Al) |
| C | 55.9 g/mol | 55.85 g/mol | Iron (Fe) |
| D | 63.1 g/mol | 63.55 g/mol | Copper (Cu) |

6. For greatest accuracy, students should use the published molar mass of each element in their calculations. Accuracy of the measured mass is limited by measurement uncertainty and manufacturing tolerance.

| Sample | Element | Calculations | Mass of Atom (g) |
|---|---|---|---|
| A | Zn | (65.38 g/mol) x (1 mol / $6.022 \times 10^{23}$ atoms) = $10.86 \times 10^{-23}$ g | $1.086 \times 10^{-22}$ g |
| B | Al | (26.98 g/mol) x (1 mol / $6.022 \times 10^{23}$ atoms) = $4.480 \times 10^{-23}$ g | $4.480 \times 10^{-23}$ g |
| C | Fe | (55.85 g/mol) x (1 mol / $6.022 \times 10^{23}$ atoms) = $9.274 \times 10^{-23}$ g | $9.274 \times 10^{-23}$ g |
| D | Cu | (63.55 g/mol) x (1 mol / $6.022 \times 10^{23}$ atoms) = $10.55 \times 10^{-23}$ g | $1.055 \times 10^{-22}$ g |

7. There are <u>two methods</u> students may use to determine the volume of the atoms. The first method relies on making physical measurements, while the second uses published data instead.

The first method involves measuring the side lengths of the one mole sample and calculating its volume. Then this total volume can be divided by Avogadro's number to find the volume of each atom.

| **Sample** | **Element** | **Calculations** | **Volume of Atom ($cm^3$)** |
|---|---|---|---|
| A | Zn | (2.14 cm x 2.12 cm x 2.03 cm) / ($6.022x10^{23}$) = $1.53x10^{-23}$ $cm^3$ | $1.53x10^{23}$ $cm^3$ |
| B | Al | (2.11 cm x 2.19 cm x 2.19 cm) / ($6.022x10^{23}$) = $1.68x10^{-23}$ $cm^3$ | $1.68x10^{-23}$ $cm^3$ |
| C | Fe | (1.90 cm x 1.99 cm x 1.90 cm) / ($6.022x10^{23}$) = $1.19x10^{-23}$ $cm^3$ | $1.19x10^{-23}$ $cm^3$ |
| D | Cu | (1.90 cm x 1.96 cm x 1.91 cm) / ($6.022x10^{23}$) = $1.18x10^{-23}$ $cm^3$ | $1.18x10^{-23}$ $cm^3$ |

The second method involves calculating the volume of one mole by dividing the atomic mass by the density. Then again, this volume is divided by Avogadro's number to find the volume of each atom.

| **Sample** | **Element** | **Calculations** | **Volume of Atom ($cm^3$)** |
|---|---|---|---|
| A | Zn | (65.38 g/mol) / (7.134 g/$cm^3$) / ($6.022x10^{23}$) = $1.522x10^{-23}$ $cm^3$ | $1.522x10^{23}$ $cm^3$ |
| B | Al | (26.98 g/mol) / (2.70 g/$cm^3$) / ($6.022x10^{23}$) = $1.66x10^{-23}$ $cm^3$ | $1.66x10^{-23}$ $cm^3$ |
| C | Fe | (55.85 g/mol) / (7.874 g/$cm^3$) / ($6.022x10^{23}$) = $1.178x10^{-23}$ $cm^3$ | $1.178x10^{-23}$ $cm^3$ |
| D | Cu | (63.55 g/mol) / (8.933 g/$cm^3$) / ($6.022x10^{23}$) = $1.181x10^{-23}$ $cm^3$ | $1.181x10^{-23}$ $cm^3$ |

8. Sample calculations based on method 2 answers: (answers converted from centimeters to picometers):

| **Sample** | **Element** | **Calculations** | **Edge Length (pm)** |
|---|---|---|---|
| A | Zn | $(1.522x10^{-23}\ cm^3)^{1/3}$ = $2.478x10^{-8}$ cm = $2.478x10^{-8}$ cm | 248 pm |
| B | Al | $(1.66x10^{-23}\ cm^3)^{1/3}$ = $2.55x10^{-8}$ cm = $2.55x10^{-8}$ cm | 255 pm |
| C | Fe | $(1.178x10^{-23}\ cm^3)^{1/3}$ = $2.275x10^{-8}$ cm = $2.275x10^{-8}$ cm | 228 pm |
| D | Cu | $(1.181x10^{-23}\ cm^3)^{1/3}$ = $2.277x10^{-8}$ cm = $2.277x10^{-8}$ cm | 228 pm |

9. Sample calculations based on previous answers: (answers expressed in picometers):

| **Sample** | **Element** | **Calculations** | **Calculated Atomic Radius (pm)** | **Accepted Atomic Radius (pm)** |
|---|---|---|---|---|
| A | Zn | 248 pm / 2 = 124 pm | 124 pm | 134 pm |
| B | Al | 255 pm / 2 = 128 pm | 128 pm | 143 pm |
| C | Fe | 228 pm / 2 = 114 pm | 114 pm | 126 pm |
| D | Cu | 228 pm / 2 = 114 pm | 114 pm | 128 pm |

10. This may be done as a lab exercise using calorimetry techniques or by looking up the specific heat in a reference table. The following values were obtained from reference data.

| Sample | Element | Specific Heat (J/g°C) | Calculations | Molar Heat Capacity (J/mol°C) |
|---|---|---|---|---|
| A | Zn | 0.390 J/g°C | (0.390 J/g°C) x (65.38 g/mol) = 25.5 J/mol°C | 25.5 J/mol°C |
| B | Al | 0.900 J/g°C | (0.900 J/g°C) x (26.98 g/mol) = 24.3 J/mol°C | 24.3 J/mol°C |
| C | Fe | 0.440 J/g°C | (0.440 J/g°C) x (55.85 g/mol) = 24.6 J/mol°C | 24.6 J/mol°C |
| D | Cu | 0.385 J/g°C | (0.385 J/g°C) x (63.55 g/mol) = 24.5 J/mol°C | 24.5 J/mol°C |

On a per unit mass basis, the specific heat data show that the amount of heat absorbed/released per 1 degree Celsius temperature change varies widely among the elements. When the heat capacity of one mole of a substance is considered instead, we see that each sample has approximately the same molar heat capacity. This result may seem surprising, but it follows from simple ideas about the nature of heat and temperature.

11. Suppose we had a sample of some unidentified element, and determined that its heat capacity was 25 J/°C. This is approximately the same as the molar heat capacity of our samples, so we could conclude that the sample contains approximately one mole. Then by measuring the mass of the sample, we would have a good estimate of the element's atomic mass (molar mass) and could identify it from a list of elements and their atomic masses.

In the more likely case that the sample was not one mole, we could find its atomic mass as follows: Suppose a 162 gram sample of an element is found to have a heat capacity of 37.0 J/°C. From question 10, we know that the heat capacity of one mole is on average 24.7 J/mol°C.

Then $$\frac{37.0\ \text{J/°C}}{24.7\ \text{J/mol°C}} = 1.50\ \text{mol}$$

This establishes that we have a 1.5 mole sample.

Finding the ratio of mass to number of moles, we find that the element has an atomic mass of approximately 108 g/mol.

$$\frac{162\ \text{g}}{1.50\ \text{mol}} = 108\ \text{g/mol}$$

We may suspect that the element is silver, or at least an element whose atomic mass is close to that of silver.

# Reference Data (metals)

| Atomic Number | Symbol | Element | Atomic Mass[1] (g/mol) | Density[2] ($g/cm^3$) | Atomic Radius[3] (pm) | Specific Heat[4] (J/g°C ) |
|---|---|---|---|---|---|---|
| 3 | Li | Lithium | 6.968 | 0.534 | 152 | 3.305 |
| 4 | Be | Beryllium | 9.012 | 1.85 | 112 | 1.925 |
| 11 | Na | Sodium | 22.99 | 0.97 | 186 | 1.235 |
| 12 | Mg | Magnesium | 24.31 | 1.74 | 160 | 1.025 |
| 13 | Al | Aluminum | 26.98 | 2.70 | 143 | 0.900 |
| 19 | K | Potassium | 39.10 | 0.89 | 227 | 0.724 |
| 20 | Ca | Calcium | 40.08 | 1.54 | 197 | 0.643 |
| 21 | Sc | Scandium | 44.96 | 2.99 | 162 | 0.540 |
| 22 | Ti | Titanium | 47.87 | 4.5 | 147 | 0.528 |
| 23 | V | Vanadium | 50.94 | 6.0 | 134 | 0.502 |
| 24 | Cr | Chromium | 52.00 | 7.15 | 128 | 0.461 |
| 25 | Mn | Manganese | 54.94 | 7.3 | 127 | 0.448 |
| 26 | Fe | Iron | 55.85 | 7.874 | 126 | 0.440 |
| 27 | Co | Cobalt | 58.93 | 8.86 | 125 | 0.440 |
| 28 | Ni | Nickel | 58.69 | 8.912 | 124 | 0.460 |
| 29 | Cu | Copper | 63.55 | 8.933 | 128 | 0.385 |
| 30 | Zn | Zinc | 65.38 | 7.134 | 134 | 0.390 |
| 31 | Ga | Gallium | 69.72 | 5.91 | 135 | 0.330 |
| 37 | Rb | Rubidium | 85.47 | 1.53 | 248 | 0.336 |
| 38 | Sr | Strontium | 87.62 | 2.64 | 215 | 0.308 |
| 39 | Y | Yttrium | 88.91 | 4.47 | 180 | 0.300 |
| 40 | Zr | Zirconium | 91.22 | 6.52 | 160 | 0.285 |

# (continued)

| Atomic Number | Symbol | Element | Atomic Mass[1] (g/mol) | Density[2] ($g/cm^3$) | Atomic Radius[3] (pm) | Specific Heat[4] (J/g°C ) |
|---|---|---|---|---|---|---|
| 41 | Nb | Niobium | 92.91 | 8.57 | 146 | 0.272 |
| 42 | Mo | Molybdenum | 95.95 | 10.2 | 139 | 0.255 |
| 43 | Tc | Technetium | 97.91 | 11 | 136 | - |
| 44 | Ru | Ruthenium | 101.1 | 12.1 | 134 | 0.243 |
| 45 | Rh | Rhodium | 102.9 | 12.4 | 134 | 0.243 |
| 46 | Pd | Palladium | 106.4 | 12.0 | 137 | 0.247 |
| 47 | Ag | Silver | 107.9 | 10.501 | 144 | 0.234 |
| 48 | Cd | Cadmium | 112.4 | 8.69 | 151 | 0.230 |
| 49 | In | Indium | 114.8 | 7.31 | 167 | 0.252 |
| 50 | Sn | Tin | 118.7 | 7.287 | 141 | 0.256 |

1 Zucker, M.A., et al. “Elemental Data Index.” *National Institute of Standards and Technology*, Dec. 2017, www.nist.gov/pml/elemental-data-index. Accessed 13 July, 2023.

2 National Center for Biotechnology Information. "Density in the Periodic Table of Elements." *PubChem*, https://pubchem.ncbi.nlm.nih.gov/periodic-table/density. Accessed 13 July, 2023.

3 Greenwood, N. N., and A. Earnshaw. *Chemistry of the Elements.* 2nd ed., Oxford, Butterworth-Heinemann, 1998.

4 *MatWeb*, Matweb LLC, www.matweb.com. Accessed 17 July 2023

| Unit Conversions |
|---|
| 1 cm = $10^{10}$ pm |
| 1 cm = 0.01 m |
| 1 m = $10^{12}$ pm |

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