Experiment 1: The Periodic Behavior of Metals

Background

Some metals readily dissolve in water, some only dissolve in acid, and some do not react with either one. How can we explain this? To address this question we need to understand the chemical reactions that are taking place.

Some metals react with water according to the following reaction:

$$2\ M(s) + 2n\ H_2O(l) \rightarrow 2n\ OH^-(aq) + n\ H_2(g) + 2\ M^{n+}(aq) \qquad (1)$$

This is an example of an *oxidation-reduction* reaction where H^+ takes an electron from the metal and is *reduced* to hydrogen gas.

$$2\ H_2O(l) \rightleftharpoons 2\ H^+(aq) + 2\ OH^-(aq) \qquad \text{(autoionization of water)}$$

$$2\ H^+(aq) + 2e^- \rightarrow H_2(g)$$

$$2\ H_2O(l) + 2e^- \rightarrow 2\ OH^-(aq) + H_2(g) \qquad (2)$$

The elemental metal loses *n* electrons and is *oxidized* to the corresponding cation.

$$M(s) \rightarrow n\ e- + M^{n+}(aq) \qquad (3)$$

Combining equations (2) and (3) and adjusting for the same number of electrons to be transferred we obtain equation (1);

$$(2\ H_2O(l) + 2\ e^- \rightarrow 2\ OH^-(aq) + H_2(g)) \times n$$

$$(M(s) \rightarrow n\ e- + M^{n+}(aq)) \times 2$$

$$2\ M(s) + 2n\ H_2O(l) \rightarrow 2n\ OH^-(aq) + n\ H_2(g) + 2\ M^{n+}(aq) \qquad (1)$$

Experimentally we can detect the presence of hydroxide ions by adding a drop of the indicator phenolphthalein: the indicator is colorless in acid solution and turns bright pink in the presence of OH- ions. We can also watch for the formation of H_2 bubbles. Either observation indicates that reaction (1) is taking place.

The occurrence of these reactions depends on the relative attractions of H^+ and the metal for the electron. Metals that have a strong tendency to get oxidized to the corresponding cation will be the best at reducing H^+ and will be able to react with water, whose concentration of H^+ is only $1.0\text{x}10^{-7}$ M.

If the metal does not react with cold water it can be tested in hot water, which increases the reaction rate. If no reaction is observed in cold water the metal will be tested with cold HCl. The reaction of a metal with HCl is as follows:

$$2\ M(s) + 2n\ H^+(aq) \rightarrow 2\ M^{n+}(aq) + n\ H_2(g) \qquad (4)$$

For those metals that don't react with cold HCl the reaction will be repeated with hot HCl. At the end of the experiment there will probably be a few metals that have not reacted at all, even with hot HCl. These metals hold their electrons so strongly that the hydrogen ion cannot remove them. They should be grouped together as the least reactive metals in the reduction activity series.

We will test seven metals: Ca, Cu, Fe, Mg, Mn, Ni, and Zn.

By measuring the reactivities of these different metals with H^+ we will be able to rank them according to their reducing activity. The more vigorous the reaction with H^+, the higher the metal M ranks in the reduction activity series:

M react w/ cold H_2O > M react w/ hot H_2O > M react w/ cold HCl > M react w/ hot HCl > M does not react at all

Thinking about the transfer of electrons that takes place in these reduction and oxidation reactions, you must try to find a correlation between the reduction activity series and one of the periodic properties listed in the following table.

Metal	1st ionization energy (kJ/mol)	2nd Ionization energy (kJ/mol)	Electronegativity (Pauling scale)	Ionic radius (picometers)
Ca	590	1145	1.00	100
Cu	745	1957	1.90	73
Fe	762	1561	1.83	61
Mg	737	1450	1.31	72
Mn	717	1508	1.55	83
Ni	737	1752	1.91	69
Zn	906	1733	1.65	74

References: All values in this table were obtained from the CRC, 85th edition. The electronegativity values (according to Pauling's electronegativity scale) assume the most common oxidation state. The values for the ionic radii assume the most common oxidation state and octahedral geometry.
The ionic radii were obtained from www.webelememts.com. The ionic radius assumes the most common oxidation state and octahedral geometry.

Experimental Procedure

Safety hazards: HCl is corrosive and can damage skin and clothing. Make sure to avoid contact with it. The solutions containing dissolved heavy metals are toxic. Avoid contact and wash hands before leaving the laboratory.

Instructions: Use the data table provided on the next page to record data and observations. Always record data in permanent ink.

1. Fill a 400 mL beaker with 250 mL of water and heat it just below 100°C. It will be used as your water bath throughout the experiment.

2. Obtain samples of all seven metals (Ca, Cu, Fe, Mg, Mn, Ni, and Zn). (size of the sample: no larger than 1/4 of an M&M)

3. Put a few granules of each metal in large labeled test tubes with about 5 mL of distilled water and a couple of drops of phenolphthalein (it works best to label the tubes with tape). Do you see H_2 bubbles form? Does the solution turn pink? For the metals that are in powder form you should wait a few minutes until the sample sediments at the bottom of the tube so that you can observe the color of the solution. Note that the transient appearance of a pink color also indicates the local formation of OH- ions. Record which metals react and note which metals do so more vigorously (how many bubbles form?). Notice that some metals will react vigorously forming many large bubbles but other metals can form very small hydrogen bubbles. Watch for both kinds!

4. Continue the experiment *only* with those elements that did not react or reacted very weakly with cold water. Place their tubes in the hot water bath and observe whether H_2 bubbles form. Record which metals react and note which metals do so more vigorously.

5. Using *only* the metals that have not reacted yet pour off all but 2mL of H_2O and add 2mL of 6M HCl. Watch for H_2 bubbles for a few minutes. Record which metals react and how vigorously they do.

6. Using *only* the metals that did not react with cold HCl put the corresponding test tubes in the hot water bath and look for any reaction for a few minutes. Record which metals react and which ones do so more vigorously.

7. Arrange the metals in order of reduction activity putting the most reactive first. The end of the list should have all the elements that did not react even with hot 6M HCl.

Waste disposal

The solutions containing the heavy metals should be disposed of in the waste containers indicated by your instructor.

Data and Observations

8. Complete the table below with the results of your observations.

	Metals that reacted	Metals that did not react	Order of reactivity + ⟶ --
Cold water test			
Hot water test			
Cold HCl test			
Hot HCl test			
Overall reactivity order + ⟶ –			

(" +" most reactive; " –" least reactive)

Student Signature ____________________________________ Date:_______

Lab Partner's Name _________________________ Instructor's initials _______

Follow-up Questions

1. Plot each the ionic radii (Table 1) versus your series of metals in order of decreasing reactivity (the order that you answered in the table of the previous page). Label your axes clearly.

2. Plot electronegativities (Table 1) versus your series of metals in order of decreasing reactivity. Label your axes clearly.

3. Plot the sum of both ionization energies (Table 1) versus your series of metals in order of decreasing reactivity. Label your axes clearly.

4. Which property correlates best with reduction activity? Explain why this is so.

5. Was the correlation perfect? If it was not, can you think of any reasons for this to be the case?

Pre-Lab Assignment—To be completed BEFORE lab!!!

Refer to Chapter 7 in your textbook to answer these questions. For unfamiliar terms, like electronegativity, look in the index or the glossary in your textbook.

1. How do you define the first ionization energy?

2. **Describe** the variation of the first ionization energy only for main group elements as:

a) The atomic number increases along a period

b) The atomic number increases along a group.

3. The first ionization energy (IE_1) for Mg is 737 kJ/mol and the second ionization energy (IE_2) is 1450 kJ/mol:

$$M + Energy \rightarrow M^{+} + e^{-} \qquad IE_1$$

$$M^{+} + Energy \rightarrow M^{2+} + e^{-} \qquad IE_2$$

How much energy does the following reaction take?

$$Mg (g) \rightarrow Mg^{2+}(g) + 2\ e^{-}$$

4. **Explain** in your own words what electronegativity means.

5. **Describe** in your own words how the electronegativity varies as

a) The atomic number increases along a period

b) The atomic number increases along a group.

6. The effective nuclear charge Z* is the amount of positive charge experienced by the outermost electrons in an atom. The inner-shell electrons shield electrons farther out from some of the nuclear charge so that the outer electrons do not experience the full nuclear charge. For most electrons Z* can be approximated as

$$\mathbf{Z^* = Z - (\text{number of inner-shell electrons})}$$

a) Do you predict Z* to be higher for Ca or for Cu?

b) Calculate Z* for both elements.