Chapter 4

Solutions to Supplementary *Check for Understanding* Problems

Energy Changes

1. Indicate whether each of the following involves primarily kinetic energy or potential energy.

   a) stretched rubber band
   b) running water
   c) stack of books
   d) person riding a bike
   e) car parked on a hill
   f) pitched baseball

Answers:

a) potential energy	d) kinetic energy
b) kinetic energy	e) potential energy
c) potential energy	f) kinetic energy

Solutions

Kinetic energy is associated with motion as is found in (b), (d) and (f). Potential energy is stored energy associated with the position of an object as in (a), (c) and (e).

2. Which physical state involves constituent particles with the highest kinetic energy?

Solution

The gas phase is associated with constituent particles having the highest kinetic energy because energy must be added as a substance moves from the solid state to the liquid state to the gas phase. This added energy is causes the constituent particles to move faster.

3. Is the condensation of a gas an exothermic or endothermic process? Explain.

Answer: exothermic

Solution

An exothermic process is one in which energy (heat) is released. The liquid state is at a lower energy level than the gas phase so energy is released as a gas condenses. It is helpful to note that the reverse process (liquid ➔ gas) is endothermic because it requires an input of heat.

4. How much energy (in kJ) is needed to heat 3.8 L of water from 22.3 °C to 100 °C?

Answer: 1.2×10^3 kJ

Solution

The amount of heat energy (q) needed is calculated from $q = m \cdot c \cdot \Delta t$. For water, the specific heat (c) equals 4.18 J/g ·°C. The temperature change (Δt) is 100 °C - 22.3 °C = 77.7 °C. The mass of water (m) in grams must be calculated from its volume using the density of water (in Table 2.3 the water density = 0.9978 g/mL at 22 °C). The solution map for this conversion is:

$L\ H_2O \rightarrow mL\ H_2O \rightarrow g\ H_2O$

This yields:

$$3.8\ \cancel{L\ H_2O} \times \frac{1\ \cancel{mL\ H_2O}}{10^{-3}\ \cancel{L\ H_2O}} \times \frac{0.9978\ g\ H_2O}{1\ \cancel{mL\ H_2O}} = 3.8 \times 10^3\ g\ H_2O$$

Substituting these values and calculating *q* gives:

$$q = (3.8 \times 10^3\ \cancel{g\ H_2O})(4.18\ J/\cancel{g\ H_2O} \times \cancel{^oC})(77.7\ \cancel{^oC}) = 1.2 \times 10^6 J$$

$$1.2\ 10^6\ \cancel{J} \times \frac{1 kJ}{10^3\ \cancel{J}} = 1.2 \times 10^3\ kJ$$

5. When 25 g of water freezes 8.4 kJ of energy is released. How much energy is required to melt a pound of ice?

Answer: 1.5×10^2 kJ

Solution

Note that is takes 8.4 kJ to melt 25 g of water so this serves as the conversion factor between grams of water and energy. The solution map is:

$lb\ H_2O \rightarrow g\ H_2O \rightarrow kJ$

$$1\ \cancel{lb\ H_2O} \times \frac{454\ \cancel{g\ H_2O}}{1\ \cancel{lb\ H_2O}} \times \frac{8.4\ kJ}{25\ \cancel{g\ H_2O}} = 1.5 \times 10^2\ kJ$$

6. Calculate the specific heat of a solid (J/g·°C) if 118 kcal of energy are needed to raise the temperature of 12.7 kg of the solid from 24 °C to 327 °C?

Answer: 0.128 J/g·°C

Solution

The specific heat (c) can be calculated by rearranging equation 4.1 to give:

$$c = \frac{q}{m\Delta t}$$

The amount of heat added (q) is 118 kcal which must be converted to joules. Recall that 1 cal equals exactly 4.184 J. The solution map is:

kcal ➔ cal ➔ J

$$118\,\cancel{\text{kcal}} \times \frac{10^3\,\cancel{\text{cal}}}{1\,\cancel{\text{kcal}}} \times \frac{4.184\,\text{J}}{1\,\cancel{\text{cal}}} = 4.94 \times 10^5\,\text{J}$$

The mass of the substance is 12.7 kg or 12.7 x 10^3 g, and the temperature change (Δt) is 327 °C - 24 °C = 303 °C. Substituting these values and calculating c gives:

$$c = \frac{4.94 \times 10^5\,\text{J}}{(12.7 \times 10^3\,\text{g})(303\,°\text{C})} = 0.128 \frac{\text{J}}{\text{g} \cdot °\text{C}}$$

7. If a 10-g sample of copper and a 10-g sample of aluminum are placed in a large container of boiling water for several minutes than then removed and quickly transferred to a large container of ice water, which metal will lose the greater amount of energy? Explain.

Answer: aluminum

Solution

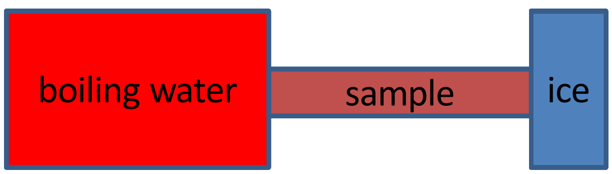
The amount of heat energy lost is calculated from $q = m \cdot c \cdot \Delta t$. Since the masses are the same (10 g) and Δt is the same (100 °C - 0 °C = 100 °C), q will be larger for the metal with the larger specific heat which is aluminum.

8. When you enter a room having a uniform temperature and touch a metal object it feels cooler than when you touch a wooden object in the room. What is your explanation (hypothesis) for this difference? What simple experiments could you do to test your hypothesis?

Solution

Hypothesis: Assuming both objects have been in the room for some time they should both be at room temperature. Because you are warmer than room temperature, heat leaves your body when you touch either object. Heat is transferred at a faster rate (your skin cools faster) when you touch the metal object than it does when you touch the wooden object because metals conduct heat much better (faster) than objects made of wood or plastic (mostly composed of nonmetals) so it feels like the metal object is cooler.

Experiment: One way to compare the ability of different materials to conduct heat is to have two containers at different temperatures connected by a sample of each material you wish to test. You could use a pot of boiling water for the higher temperature and an ice cube (or other ice mold) for the lower temperature. The samples of different materials should be exactly the same in size and shape (see figure below).



When this arrangement is created, heat will be transferred from the boiling water to the ice. By measuring the time it takes to melt the ice, or how much ice melts in a given time, you can determine which materials conduct heat more effectively.

Chemical Reactions

1. Convert each of the following word equations into a chemical equation and then balance it. Indicate the physical state of each reactant and product.

a) phosphoric acid + calcium hydroxide → water + calcium phosphate

b) ammonium nitrate → nitrogen gas + water + oxygen gas

Answers:

a) $2H_3PO_4(aq) + 3Ca(OH)_2(s) \rightarrow 6H_2O(l) + Ca_3(PO_4)_2(s)$

b) $2NH_4NO_3(s) \rightarrow 2N_2(g) + 4H_2O(l) + O_2(g)$

Solutions

First, write the chemical formula for each reactant and product, along with its physical state. Then use whole-number coefficients in front of the reactant/product formulas to balance atoms on both sides of the equation.

a) Reactant formulas:

phosphoric acid - The name indicates an oxoacid (no *hydro*- prefix) based on the anion phosphate (PO_4^{3-}). Thus, three H^+ ions are needed to balance by the charge on the anion and the correct formula is H_3PO_4(aq). Note that oxoacids are generally used as an aqueous solution and are rarely used in pure form.

calcium hydroxide - The metal cation is Ca^{2+}. The polyatomic anion formula is OH^-. It takes two hydroxides to balance the charge on the cation so the compound formula is $Ca(OH)_2$(s). The solid state is used since there is no information to suggest that this is not the pure compound.

Product formulas:

water - H_2O(l)

calcium phosphate - The metal cation is Ca^{2+}. The anion formula is PO_4^{3-}. Use the value of the anion charge as the subscript for the cation and use the value of the cation charge as the subscript for the anion. The compound formula is $Ca_3(PO_4)_2$. This ionic compound is formed in the presence of water so you must consider if this compound dissolves readily in water. The combination of +2 and -3 ion charges suggest this will be an insoluble compound so the solid state is used.

This results in the equation:

$$H_3PO_4(aq) \quad + \quad Ca(OH)_2(s) \quad \rightarrow \quad H_2O(l) \quad + \quad Ca_3(PO_4)_2(s)$$

Notice that the polyatomic phosphate ion does not undergo any change in composition in this reaction. This means that you can balance PO_4^{3-} units just like an individual atom. Since there are 2 phosphate ions on the product side, a coefficient of 2 is needed in front of H_3PO_4 on the reactant side. To balance calcium atoms, place a coefficient of 3 in front of $Ca(OH)_2$ on the reactant side. There are now 12 hydrogen atoms on the reactant side and only 2 on the product side so a cooefficient of 6 is needed in front of water on the product side. Notice that this also balances the oxygen atoms, a total of 14 on each side of the equation. The balanced equation is:

$$2H_3PO_4(aq) \quad + \quad 3Ca(OH)_2(s) \quad \rightarrow \quad 6H_2O(l) \quad + \quad Ca_3(PO_4)_2(s)$$

b) Reactant formula:

ammonium nitrate - The metal cation is NH_4^+. The polyatomic anion formula is NO_3^-. Since the ion charges are the same, it takes one cation to balance the charge on the anion and the compound formula is NH_4NO_3. A pure ionic compound is expected to be a solid.

Product formulas:

nitrogen gas - This element exists as a diatomic molecule with the formula $N_2(g)$.

water - $H_2O(l)$

oxygen gas - This element exists as a diatomic molecule with the formula $O_2(g)$.

This results in the unbalanced equation

$$NH_4NO_3(s) \rightarrow N_2(g) + H_2O(l) + O_2(g) \quad \text{(N and O atoms balanced)}$$

Notice that the nitrogen atoms and oxygen atoms are balanced, so balance the hydrogen atoms. Place a coefficient of 2 in front of H_2O to balanced hydrogen atoms, but now there are 3 oxygen atoms on the reactant side and four on the product side.

$$NH_4NO_3(s) \rightarrow N_2(g) + 2H_2O(l) + O_2(g) \quad \text{(N and H atoms balanced)}$$

A coefficient of ½ in front of O_2 will balance oxygen atoms.

$$NH_4NO_3(s) \rightarrow N_2(g) + 2H_2O(l) + \tfrac{1}{2}O_2(g) \quad \text{(all atoms balanced)}$$

The fractional coefficient in front of O_2 can be converted to the smallest whole number by multiplying by 2. This requires that all other coefficients be multiplied by 2 in order to retain the atom balance. The resulting balanced equation is:

$$2NH_4NO_3(s) \rightarrow 2N_2(g) + 4H_2O(l) + O_2(g)$$

2. Balance each of the following chemical equations.

a) $CaC_2(s) + H_2O(l) \rightarrow Ca(OH)_2(s) + C_2H_2(g)$

b) $NO_2(g) + H_2O(l) \rightarrow HNO_3(aq) + NO(g)$

c) $Fe_2O_3(s) + CO(s) \rightarrow Fe(s) + CO_2(g)$

d) $H_2O_2(aq) \rightarrow H_2O(l) + O_2(g)$

Answers:

a) $CaC_2(s) + 2H_2O(l) \rightarrow Ca(OH)_2(s) + C_2H_2(g)$

b) $3NO_2(g) + H_2O(l) \rightarrow 2HNO_3(aq) + NO(g)$

c) $Fe_2O_3(s) + 3CO(s) \rightarrow 2Fe(s) + 3CO_2(g)$

d) $2H_2O_2(aq) \rightarrow 2H_2O(l) + O_2(g)$

Solutions

a) Initially the carbon atoms and calcium atoms are balanced but the hydrogen and oxygen atoms are not.

$$CaC_2(s) + H_2O(l) \rightarrow Ca(OH)_2(s) + C_2H_2(g)$$

2 atoms ← C → 2 atoms

1 atom ← Ca → 1 atom

2 atoms ← H → 4 atoms

1 atom ← O → 2 atoms

Placing a coefficient of 2 in front of water will balance both the hydrogen and oxygen atoms.

$$CaC_2(s) + 2H_2O(l) \rightarrow Ca(OH)_2(s) + C_2H_2(g)$$

b) Initially no atoms are balanced.

$$NO_2(g) + H_2O(l) \rightarrow HNO_3(aq) + NO(g)$$

1 atom ← N → 2 atoms

2 atoms ← H → 1 atom

3 atoms ← O → 4 atoms

Also note that any new coefficient will change the number of two or three different atoms. Start by placing a coefficient of 2 in front of HNO_3 to balance the hydrogen atoms. This results in the following.

$$NO_2(g) + H_2O(l) \rightarrow 2HNO_3(aq) + NO(g)$$

1 atom ← N → 3 atoms

2 atoms ← H → 2 atoms

3 atoms ← O → 7 atoms

Next place a coefficient of 3 in front of NO_2 to balance the nitrogen atoms. This also balances the oxygen atoms and results in a balanced equation.

$$3NO_2(g) + H_2O(l) \rightarrow 2HNO_3(aq) + NO(g)$$

3 atoms ← N → 3 atoms

2 atoms ← H → 2 atoms

7 atoms ← O → 7 atoms

c) Initially only the carbon atoms are balanced.

$$Fe_2O_3(s) + CO(s) \rightarrow Fe(s) + CO_2(g)$$

1 atom ← C → 1 atom

2 atoms ← Fe → 1 atom

4 atoms ← O → 2 atoms

Placing a coefficient of 2 in front of Fe will balance the iron atoms.

$$Fe_2O_3(s) + CO(s) \rightarrow 2Fe(s) + CO_2(g)$$

1 atom ← C → 1 atom

2 atoms ← Fe → 2 atoms

4 atoms ← O → 2 atoms

Any attempt to add more oxygen atoms to the product side by changing the coefficient in front of CO_2 will upset the balance of carbon atoms so the same coefficient must be placed in front of CO as well. A coefficient of 3 will balance both the oxygen atoms and carbon atoms.

$$Fe_2O_3(s) + 3CO(s) \rightarrow 2Fe(s) + 3CO_2(g)$$

3 atoms ← C → 3 atoms

2 atoms ← Fe → 2 atoms

6 atoms ← O → 6 atoms

d) Initially the hydrogen atoms are balanced but the oxygen atoms are not.

$$H_2O_2(aq) \rightarrow H_2O(l) + O_2(g)$$

2 atoms ← H → 2 atoms

2 atoms ← O → 3 atoms

Placing a coefficient of ½ in front of O_2 will balance oxygen atoms.

$$H_2O_2(aq) \rightarrow H_2O(l) + \tfrac{1}{2}O_2(g)$$

2 atoms ← H → 2 atoms

2 atoms ← O → 2 atoms

The fractional coefficient in front of O_2 can be converted to the smallest whole number by multiplying by 2. This requires that all other coefficients be multiplied by 2 in order to retain the atom balance. The resulting balanced equation is:

$$2H_2O_2(aq) \rightarrow 2H_2O(l) + O_2(g)$$

3. If ammonia gas and 0.128 g of hydrogen chloride gas react to form 0.188 g of ammonium chloride, what mass of ammonia reacted?

Answer: 0.060 g

Solution

The given information is:

$$\begin{array}{ccccc} NH_4(g) & + & HCl(g) & \rightarrow & HNH_4Cl(s) \\ & & 0.128\ g & & 0.188\ g \end{array}$$

Since one expects the mass of the products in a chemical reaction to equal the mass of the reactants, the mass of ammonia equals 0.188 g - 0.128 g = 0.060 g.

4. What does the notation '(aq)' signify about a reactant or product in a chemical equation?

Solution

The *(aq)* designation stands for aqueous solution and indicates that the substance is dissolved in water.

5. Classify each of the following reactions as combination, decomposition, combustion, single displacement or double displacement, then complete and balance each equation. Indicate the physical state of each product.

a) $K_3PO_4(aq) + BaCl_2(aq) \rightarrow$

b) $Al(s) + H_2SO_4(aq) \rightarrow$

c) $C_4H_9OH(l) + O_2(g) \rightarrow$

d) $CuO(s) + HNO_3(aq) \rightarrow$

e) $Al(s) + Br_2(l) \rightarrow$

Answers: a) double displacement $2K_3PO_4(aq) + 3BaCl_2(aq) \rightarrow 6KCl(aq) + Ba_3(PO_4)_2(s)$

b) single displacement $2Al(s) + 3H_2SO_4(aq) \rightarrow 3H_2(g) + Al_2(SO_4)_3(aq)$

c) combustion $C_4H_9OH(l) + 6O_2(g) \rightarrow 4CO_2(g) + 5H_2O(l)$

d) double displacement $CuO(s) + 2HNO_3(aq) \rightarrow Cu(NO_3)_2(aq) + H_2O(l)$

e) combination $2Al(s) + 3Br_2(l) \rightarrow 2AlBr_3(aq)$

Solutions

a) This reaction between two dissolved ionic compounds should suggest a double displacement reaction of the general form AB + CD → AD + CB. In this case the two metal ions, potassium (K^+) and barium (Ba^{2+}), in the reactants switch places to form an ionic compound between potassium ion and chloride ion (Cl^-) and an ionic compound between barium ion and phosphate ion (PO_4^{3-}). Therefore, the product formulas are KCl and $Ba_3(PO_4)_2$. The combination of a +1 cation and a -1 anion is expected to soluble while the combination of a +2 cation and a -3 anion is expected to insoluble . This results in the unbalanced equation:

$$K_3PO_4(aq) + BaCl_2(aq) \rightarrow KCl(aq) + Ba_3(PO_4)_2(s)$$

To balance this equation, place a coefficient of 2 in front of K_3PO_4 to balance phosphate units. This requires a coefficient of 6 in front of KCl to balanced potassium atoms. Finally, a coefficient of 3 in front of $BaCl_2$ will balance both the barium atoms and the chlorine atoms. The balanced equation is:

$$2K_3PO_4(aq) + 3BaCl_2(aq) \rightarrow 6KCl(aq) + Ba_3(PO_4)_2(s)$$

b) This reaction between an elemental form and an oxoacid should suggest a single displacement reaction of the general form A + BC → AC + B where A and B are elemental forms and BC and AC are compounds. The metal aluminum (Al) displaces hydrogen in the oxoacid to form elemental hydrogen, $H_2(g)$, and an ionic compound consisting of aluminum ions (Al^{3+}) ions and sulfate (SO_4^{2-}) ions. This means that the formula of the compound formed between Al^{3+} and SO_4^{2-} is $Al_2(SO_4)_3$. Although this ionic compound contains a +3 cation and a -2 anion, suggesting it is insoluble, compounds containing sulfate tend to be soluble. The unbalanced equation is:

$$Al(s) + H_2SO_4(aq) \rightarrow H_2(g) + Al_2(SO_4)_3(aq)$$

To balance this equation, place a coefficient of 2 in front of Al to balance aluminum atoms and place a coefficient of 3 in front of H_2SO_4 to balance sulfate units. Finally, a coefficient of 3 in front of H_2 will balance both the hydrogen atoms. The balanced equation is:

$$2Al(s) + 3H_2SO_4(aq) \rightarrow 3H_2(g) + Al_2(SO_4)_3(aq)$$

c) This is a reaction between a $C_xH_yO_z$ compound and oxygen so it is a combustion reaction that forms $CO_2(g)$ and $H_2O(l)$ as products.

$$C_4H_9OH(l) + O_2(g) \rightarrow CO_2(g) + H_2O(l) \qquad \text{(unbalanced)}$$

Start by balancing the carbon atoms by putting a coefficient of 4 in front of CO_2. Since there are 10 H atoms on the reactant side and only 2 H atoms on the product side, a coefficient of 2 in front of H_2O will balance hydrogen atoms.

$$C_4H_9OH(g) + O_2(g) \rightarrow 4CO_2(g) + 5H_2O(l) \qquad \text{(C and H atoms balanced)}$$

Finally, balance the oxygen atoms. Since there are 3 O atoms on the reactant side and 13 O atoms on the product side, multiplying O_2 by 6 will balance oxygen atoms.

$$C_4H_9OH(g) + 6O_2(g) \rightarrow 4CO_2(g) + 5H_2O(l) \qquad \text{(all atoms balanced)}$$

d) This reaction between an ionic compound and an oxoacid should suggest a double displacement reaction of the general form AB + CD → AD + CB. In this case the metal copper (Bi) and hydrogen in the reactants switch places to form water and an ionic compound between copper and nitrate. Notice that the ionic compound reactant (CuO) involves Cu^{2+}. Since nitrate ion has a -1 charge, the correct formula for the ionic compound formed is $Cu(NO_3)_2$. This combination of a +2 cation and a -1 anion is expected to soluble. This results in the unbalanced equation:

$$CuO(s) + HNO_3(aq) \rightarrow Cu(NO_3)_2(aq) + H_2O(l)$$

Notice that the copper atoms and oxygen atoms are balanced. To balance this equation, place a coefficient of 2 in front of HNO_3 to balance hydrogen atoms and the nitrate units. The balanced equation is:

$$CuO(s) + 2HNO_3(aq) \rightarrow Cu(NO_3)_2(aq) + H_2O(l)$$

e) The reaction of two elemental forms should suggest a combination reaction. Since a metal (Al) is reacting with a nonmetal (Br_2) an ionic compound will form. Aluminum is expected to form an Al^{3+} ion and bromine is expected to form a Br^- ion. The correct formula for the ionic compound formed is $AlBr_3$. This combination of a +3 cation and a -1 anion is expected to soluble. This results in the unbalanced equation:

$$Al(s) + Br_2(l) \rightarrow AlBr_3(aq)$$

The aluminum atoms are balanced but there are 2 bromine atoms on the reactant side and 3 bromine atoms on the product side. Multiplying Br_2 by 3/2 will balance bromine atoms.

$$Al(s) + 3/2Br_2(l) \rightarrow AlBr_3(aq)$$

The fractional coefficient in front of Br_2 can be converted to the smallest whole number by multiplying by 2. This requires that all other coefficients be multiplied by 2 in order to retain the atom balance. The resulting balanced equation is:

$$2Al(s) + 3Br_2(l) \rightarrow 2AlBr_3(aq)$$