Determination of Molar Mass by Freezing-Point Depression

OBJECTIVES:

- Gain familiarity with colligative properties of nonelectrolyte solutions
- Find the molar mass of a solute by the method of freezing-point depression
- Evaluate the accuracy of the method by comparison to a molar mass calculated from a molecular formula.

DISCUSSION:

When a solution forms, the freezing point of the solution is lower than the freezing point of the pure solvent. The magnitude of this *freezing-point depression* (ΔT_f) depends only on the number ratio of solvent and solute molecules (or ions) in the solution, not on their chemical identity. This makes ΔT_f one of the *colligative properties* of solutions.

If we express the solution concentration as a *molality* $\left(\text{defined so that } 1\ m = \dfrac{1\text{ mol solute}}{1\text{ kg solvent}}\right)$, then the freezing-point depression follows a simple direct proportionality relationship:

$$\Delta T_f = K_f m \qquad (1)$$

where the proportionality constant, K_f, is called the molal freezing-point depression constant. Lauric acid (the solvent in this experiment) has a reported K_f = 3.9 °C·kg/mol = 3.9 °C/m.

In this experiment, you will determine the freezing point of the pure solvent, $CH_3(CH_2)_{10}COOH$ (lauric acid). You will then find the freezing point of a lauric acid solution that contains a measured mass of solute C_6H_5COOH (benzoic acid) and determine the freezing-point depression. Using the experimental ΔT_f value and the reported K_f value in equation (1) will enable you to find the amount (in moles) of benzoic acid in your solution. This value, along with the known mass of benzoic acid, leads to the molar mass determination.

PROCEDURE:

Part I–Freezing point of pure lauric acid

1. Set up two water baths (one at about 80 °C and one at room temperature) using 400-mL beakers filled to about 300 mL. Obtain a sample of pure lauric acid in a sealed test tube. Remove the stopper with care and then clamp this tube in a hot water bath to melt the solid lauric acid.
2. Once the lauric acid has melted completely, insert a thermometer or temperature probe into the hot liquid lauric acid. Wait for the temperature reading to achieve a steady value above 50 °C.
3. Remove the test tube/thermometer assembly from the hot bath and clamp it suspended in the room temperature bath. Insure that the water level outside the test tube is higher than the lauric acid level inside.
4. Read and record the temperature every 20 s for ten minutes. If the initial temperature is below 50 °C, begin again.
5. Continuously stir the lauric acid during cooling, using a slight up-down motion of the thermometer. When the lauric acid freezes solid, stop stirring so as not to break the thermometer or the test tube.

6. Re-melt the lauric acid sample in the hot bath to free the thermometer. Carefully wipe any excess liquid from the probe with a paper towel, reseal the lauric acid test tube, and return it to the rack.
7. Prepare a graph of the pure lauric acid temperature *vs.* time. This type of graph is called a *cooling curve*. The freezing point of lauric acid should be apparent from the graph. Check your result with your instructor.

Part II–Freezing point of lauric acid solution of benzoic acid

8. Obtain a sealed test tube containing a mixture of benzoic acid in lauric acid. Record the masses of benzoic acid and lauric acid exactly as they appear on the label of your tube.
9. Repeat steps 2-7 to establish the cooling curve of this mixture. Make a record of the temperature at which solid crystals first appear in the test tube.
10. To determine the freezing point temperature of your benzoic acid-lauric acid solution, you will need to find the temperature at which the mixture first started to freeze. Recognize that as one component freezes out of the liquid phase, the solution composition changes, which then lowers the freezing point of the remaining solution–a continual process.

DATA ANALYSIS:

1. Calculate the freezing-point depression of the benzoic/lauric acid solution. Remember that $\Delta T_f = T_{f,\,pure} - T_{f,\,solution}$.
2. The value of the molal freezing-point depression constant of lauric acid has been determined: $K_f = \dfrac{3.9\ °C \cdot \text{kg lauric acid}}{\text{mol solute}}$. Use this fact and the relationship $\Delta T_f = K_f \cdot m$ (where m is the molal concentration) to calculate the experimental molal concentration (also called *molality*) of your benzoic/lauric acid solution in mol/kg units.
3. Calculate the amount (in mol units) of benzoic acid solute present in your solution, using the mass of lauric acid recorded from the mixture label and your result from step 2 above.
4. Calculate your experimental value of the molar mass of benzoic acid, using the mass of benzoic acid recorded from the mixture label and your result from step 3 above.
5. Calculate the expected value of the benzoic acid molar mass from its formula: C_6H_5COOH.
6. Calculate a percent error value to compare your experimental molar mass to the expected molar mass of benzoic acid.

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Prelaboratory Assignment

For full credit, show the detailed steps of each calculation below. Use more paper if needed.

1. The freezing point of diet soda is higher than the freezing point of regular soda, but lower than 0 °C, the freezing point of pure water.
   a) Explain why both diet and regular soda freeze at temperatures lower than 0 °C.

   b) Why does diet soda freeze at a higher temperature that regular soda?

2. In order to find the molar mass of an unknown compound, a research scientist prepared a solution of 0.930 g of unknown in 125 g of a solvent. The pure solvent had a freezing point of 74.2 °C, and the solution had a freezing point of 73.4 °C. Given the solvent's freezing-point depression constant, K_f = 5.50 °C/m, find the molar mass of the unknown.

3. The freezing point of a 1 molal aqueous solution of the nonelectrolyte ethylene glycol (the principal constituent of automotive antifreeze) is about –2 °C. The freezing point of a 1 molal aqueous solution of NaCl, a strong electrolyte, is about –4 °C. If freezing-point depression is a colligative property, it should depend only on the concentration of dissolved particles. Explain this apparent discrepancy.

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Data Table 1. Pure lauric acid

time (s)	temperature (°C)	time (s)	temperature (°C)	time (s)	temperature (°C)
0		220		440	
20		240		460	
40		260		480	
60		280		500	
80		300		520	
100		320		540	
120		340		560	
140		360		580	
160		380		600	
180		400		620	
200		420		640	

lauric acid in mixture ________________g **benzoic acid _____________________g**

Data Table 2. Benzoic/lauric acid mixture

time (s)	temperature (°C)	time (s)	temperature (°C)	time (s)	temperature (°C)
0		220		440	
20		240		460	
40		260		480	
60		280		500	
80		300		520	
100		320		540	
120		340		560	
140		360		580	
160		380		600	
180		400		620	
200		420		640	

Calculations

Freezing-point depression of the benzoic/lauric acid solution:

Molal concentration (also called *molality*) of benzoic/lauric acid solution:

Amount of benzoic acid solute:

Molar mass of benzoic acid (experimental value):

Molar mass of benzoic acid (expected value):

Molar mass percent error:

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Postlaboratory Assignment

For full credit, show the detailed steps of each calculation below. Use more paper if needed.

1. The freezing point of a solvent is 87.0 °C. When a 0.163-g sample of $C_7H_6O_2$ was added to 4.18 g of the solvent, the solution had a freezing point of 82.5 °C. Find K_f for the solvent.

2. Given a compound's molar mass (99 g/mol) and elemental percent composition (48.5% C, 5.05% H, 14.1% N, and 32.3% O by mass), determine the compound's molecular formula.

3. Draw a Lewis structure of the compound described in question 2. In the correct structure, all atoms obey the octet rule and have zero formal charge.