Learning Objectives

- Define Melting, Freezing, and Sublimation

Depending on the surrounding conditions, normal matter usually exists as one of three phases: solid, liquid, or gas.

A phase change is a physical process in which a substance goes from one phase to another. Usually the change occurs when adding or removing heat at a particular temperature, known as the melting point or the boiling point of the substance. The melting point is the temperature at which the substance goes from a solid to a liquid (or from a liquid to a solid). The boiling point is the temperature at which a substance goes from a liquid to a gas (or from a gas to a liquid). The nature of the phase change depends on the direction of the heat transfer. Heat going into a substance changes it from a solid to a liquid or a liquid to a gas. Removing heat from a substance changes a gas to a liquid or a liquid to a solid.

Two key points are worth emphasizing. First, at a substance’s melting point or boiling point, two phases can exist simultaneously. Take water (H$_2$O) as an example. On the Celsius scale, H$_2$O has a melting point of 0°C and a boiling point of 100°C. At 0°C, both the solid and liquid phases of H$_2$O can coexist. However, if heat is added, some of the solid H$_2$O will melt and turn into liquid H$_2$O. If heat is removed, the opposite happens: some of the liquid H$_2$O turns into solid H$_2$O. A similar process can occur at 100°C: adding heat increases the amount of gaseous H$_2$O, while removing heat increases the amount of liquid H$_2$O (Figure 1).

Figure 1: The Boiling Point of Water. Nucleate boiling of water over a kitchen stove burner. from Wikipedia.

Water is a good substance to use as an example because many people are already familiar with it. Other substances have melting points and boiling points as well.

Second, the temperature of a substance does not change as the substance goes from one phase to another. In other words, phase changes are isothermal (isothermal means "constant temperature"). Again, consider H$_2$O as an example. Solid water (ice) can exist at 0°C. If heat is added to ice at 0°C, some of the solid changes phase to make liquid, which is also at 0°C. Remember, the solid and liquid phases of H$_2$O can coexist at 0°C. Only after all of the solid has melted into liquid does the addition of heat change the temperature of the substance.
For each phase change of a substance, there is a characteristic quantity of heat needed to perform the phase change per gram (or per mole) of material. The heat of fusion ($\Delta H_{\text{fus}}$) is the amount of heat per gram (or per mole) required for a phase change that occurs at the melting point. The heat of vaporization ($\Delta H_{\text{vap}}$) is the amount of heat per gram (or per mole) required for a phase change that occurs at the boiling point. If you know the total number of grams or moles of material, you can use the $\Delta H_{\text{fus}}$ or the $\Delta H_{\text{vap}}$ to determine the total heat being transferred for melting or solidification using these expressions:

$$\text{heat} = n \times \Delta H_{\text{fus}} \label{Eq1a}$$

where \(n\) is the number of moles and \(\Delta H_{\text{fus}}\) is expressed in energy/mole or

$$\text{heat} = m \times \Delta H_{\text{fus}} \label{Eq1b}$$

where \(m\) is the mass in grams and \(\Delta H_{\text{fus}}\) is expressed in energy/gram.

For the boiling or condensation, use these expressions:

$$\text{heat} = n \times \Delta H_{\text{vap}} \label{Eq2a}$$

where \(n\) is the number of moles and \(\Delta H_{\text{vap}}\) is expressed in energy/mole or

$$\text{heat} = m \times \Delta H_{\text{vap}} \label{Eq2b}$$

where \(m\) is the mass in grams and \(\Delta H_{\text{vap}}\) is expressed in energy/gram.

Remember that a phase change depends on the direction of the heat transfer. If heat transfers in, solids become liquids, and liquids become solids at the melting and boiling points, respectively. If heat transfers out, liquids solidify, and gases condense into liquids.

Example $\PageIndex{1}$

How much heat is necessary to melt 55.8 g of ice (solid H$_2$O) at 0°C? The heat of fusion of H$_2$O is 79.9 cal/g.

**SOLUTION**

We can use the relationship between heat and the heat of fusion (Eq. $\PageIndex{1}$b) to determine how many joules of heat are needed to melt this ice:

$$\text{heat} = m \times \Delta H_{\text{fus}} \quad [4\text{pt}] \quad = (55.8\text{ g}) \times \frac{79.9 \text{ cal}}{\text{g}} = 4,460 \text{ cal}$$

Exercise $\PageIndex{1}$

How much heat is necessary to vaporize 685 g of H$_2$O at 100°C? The heat of vaporization of H$_2$O is 540 cal/g.

Table $\PageIndex{1}$ lists the heats of fusion and vaporization for some common substances. Note the units on these quantities; when you use these values in problem solving, make sure that the other variables in your calculation are expressed in units consistent with the units in the specific heats or the heats of fusion and vaporization.
Table \(\PageIndex{1}\): Heats of Fusion and Vaporization for Selected Substances

<table>
<thead>
<tr>
<th>Substance</th>
<th>(\Delta H_{\text{fus}}) (cal/g)</th>
<th>(\Delta H_{\text{vap}}) (cal/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>aluminum (Al)</td>
<td>94.0</td>
<td>2,602</td>
</tr>
<tr>
<td>gold (Au)</td>
<td>15.3</td>
<td>409</td>
</tr>
<tr>
<td>iron (Fe)</td>
<td>63.2</td>
<td>1,504</td>
</tr>
<tr>
<td>water (H_2O)</td>
<td>79.9</td>
<td>540</td>
</tr>
<tr>
<td>sodium chloride (NaCl)</td>
<td>123.5</td>
<td>691</td>
</tr>
<tr>
<td>ethanol (C_2H_5OH)</td>
<td>45.2</td>
<td>200.3</td>
</tr>
<tr>
<td>benzene (C_6H_6)</td>
<td>30.4</td>
<td>94.1</td>
</tr>
</tbody>
</table>

Looking Closer: Sublimation

There is also a phase change where a solid goes directly to a gas:

\[
\text{solid} \rightarrow \text{gas} \label{Eq3}
\]

This phase change is called sublimation. Each substance has a characteristic heat of sublimation associated with this process. For example, the heat of sublimation \(\Delta H_{\text{sub}}\) of \(\text{H}_2\text{O}\) is 620 cal/g.

We encounter sublimation in several ways. You may already be familiar with dry ice, which is simply solid carbon dioxide (CO_2). At \(-78.5^\circ\text{C} (-109^\circ\text{F})\), solid carbon dioxide sublimes, changing directly from the solid phase to the gas phase:

\[
\text{CO}_2(\text{s}) \xrightarrow{-78.5^\circ\text{C}} \text{CO}_2(\text{g}) \label{Eq4}
\]

Solid carbon dioxide is called dry ice because it does not pass through the liquid phase. Instead, it does directly to the gas phase. (Carbon dioxide can exist as liquid but only under high pressure.) Dry ice has many practical uses, including the long-term preservation of medical samples.

Even at temperatures below 0°C, solid H_2O will slowly sublime. For example, a thin layer of snow or frost on the ground may slowly disappear as the solid H_2O sublimes, even though the outside temperature may be below the freezing point of water. Similarly, ice cubes in a freezer may get smaller over time. Although frozen, the solid water slowly sublimes, redepositing on the colder cooling elements of the freezer, which necessitates periodic defrosting (frost-free freezers minimize this redeposition). Lowering the temperature in a freezer will reduce the need to defrost as often.

Under similar circumstances, water will also sublime from frozen foods (e.g., meats or vegetables), giving them an unattractive, mottled appearance called freezer burn. It is not really a “burn,” and the food has not necessarily gone bad, although it looks unappetizing. Freezer burn can be minimized by lowering a freezer’s temperature and by wrapping
foods tightly so water does not have any space to sublime into.

Melting Point

Solids are similar to liquids in that both are condensed states, with particles that are far closer together than those of a gas. However, while liquids are fluid, solids are not. The particles of most solids are packed tightly together in an orderly arrangement. The motion of individual atoms, ions, or molecules in a solid is restricted to vibrational motion about a fixed point. Solids are almost completely incompressible and are the densest of the three states of matter.

As a solid is heated, its particles vibrate more rapidly as the solid absorbs kinetic energy. Eventually, the organization of the particles within the solid structure begins to break down and the solid starts to melt. The melting point is the temperature at which a solid changes into a liquid. At its melting point, the disruptive vibrations of the particles of the solid overcome the attractive forces operating within the solid. As with boiling points, the melting point of a solid is dependent on the strength of those attractive forces. Sodium chloride $\text{NaCl}$ is an ionic compound that consists of a multitude of strong ionic bonds. Sodium chloride melts at $801 \, ^\circ \text{C}$. Ice, a molecular compound whose molecules are held together by hydrogen bonds, has its melting point at $0 \, ^\circ \text{C}$. Though hydrogen bonds are the strongest of the intermolecular forces, the strength of hydrogen bonds is much less than that of ionic bonds. The melting point of ice is $0 \, ^\circ \text{C}$.

The melting point of a solid is the same as the freezing point of the liquid. At that temperature, the solid and liquid states of the substance are in equilibrium. For water, this equilibrium occurs at $0 \, ^\circ \text{C}$.

\[ \text{H}_2\text{O} \left( s \right) \rightleftharpoons \text{H}_2\text{O} \left( l \right) \]

We tend to think of solids as those materials that are solid at room temperature. However, all materials have melting points of some sort. Gases become solids at extremely low temperatures, and liquids will also become solid if the temperature is low enough. The table below gives the melting points of some common materials.

<table>
<thead>
<tr>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
</tr>
<tr>
<td>Oxygen</td>
</tr>
<tr>
<td>Diethyl ether</td>
</tr>
<tr>
<td>Ethanol</td>
</tr>
<tr>
<td>Water</td>
</tr>
<tr>
<td>Pure silver</td>
</tr>
<tr>
<td>Pure gold</td>
</tr>
<tr>
<td>Iron</td>
</tr>
</tbody>
</table>
Exercise \(\PageIndex{2}\)

a. Explain what happens when heat flows into or out of a substance at its melting point or boiling point.

b. How does the amount of heat required for a phase change relate to the mass of the substance?

Answer a

The energy goes into changing the phase, not the temperature.

Answer b

The amount of heat is a constant per gram of substance.

Key Takeaway

• There is an energy change associated with any phase change.

Summary

• Sublimation is the change of state from a solid to a gas without passing through the liquid state.
• Deposition is the change of state from a gas to a solid.
• Carbon dioxide is an example of a material that easily undergoes sublimation.
• The melting point is the temperature at which a solid changes into a liquid.
• Intermolecular forces have a strong influence on melting point.

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