PHASES OF MATTER AND PHASE TRANSITIONS

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Theory recap

Phases of matter. The three most common phases of matter that are constantly around us are solid, liquid and gas. Let us discuss their properties in a bit more detail.

Gas. The most familiar gas is air. A gas does not have a particular shape. For example if you take an empty bottle (really empty, even without air) and fill it with gas, the gas will take the shape of the bottle. Even more than that, gas will spread out in the whole volume of the bottle, even if initially it was contained in a smaller volume. If instead of the bottle you fill a room with the same amount of gas, it will still take up the whole volume. So gas easily changes shape and volume.

Why does gas behave like this? Remember that all matter around us is built out of tiny atoms and molecules. In a gas atoms or molecules are quite far from each other and almost do not interact with each other. They just fly all over the container and occasionally collide with each other or the walls of the container. It is then easy to understand why gases take up the whole volume provided to them. Atoms or molecules of gas will fly somewhere until they reach a wall, which means taking up the whole space.

Liquid. We are all familiar with liquid water aas well as other liquids, such as vegetable oil, gasoline, etc. On one hand liquids are similar to gases: they also take the shape of any bottle you pour them into. But on the other hand if you pour half a gallon of water into a gallon jug the water will not fill the jug completely. So liquids have particular volume (which is really hard to change) but easily change shape.

This behavior can also be understood from the point of view of atoms and molecules. They have a property that they attract each other when they are not directly in contact. What if they are located closer to each other and interact stronger than in a gas? Now they don't want to move too far from each other and instead of just flying around individually atoms and molecules tend to stay together. This explains why liquid has a particular volume. But atoms and molecules still move around each other, they just don't go too far. This explains why shape of the liquid is variable.

Solid. Most of the objects we interact with are solid: a table, a car, a laptop. Their most characteristic property is that they have a certain shape and volume. If you put a piece of metal into a bottle, nothing would happen to its shape or volume.

In solid objects atoms and molecules are interacting even stronger than in liquids. As a result, they are forced to stay in a particular place. A perfect example of a solid is a crystal. In a crystal atoms are placed in a regular lattice and cannot move to other places. Because of this crystal has a particular shape. You may ask: what about kinetic energy of the atoms? Since temperature is a measure of average internal kinetic energy and we know that solids have temperature, how can atoms not move? The answer is that they move, but just a little. They oscillate about their equilibrium positions and cannot get far from these positions.

Phase transitions. If some object is a solid, can it be made into a liquid or even into gas? In many cases the answer is yes. Think about water, for instance. Solid water is ice. At 0°C ice melts and becomes liquid water. If we continue increasing its temperature, at 100°C water boils and evaporates which means that it turns into vapor. Now if we go in the opposite direction and lower temperature starting from hot vapor, at 100°C vapor will condense which means it will become a liquid. And at 0°C liquid water freezes to become ice. Here we see that water exists in all three phases: solid (ice), liquid and gas (vapor).

For water it is very familiar, but there are many other examples. For instance, we are used to metals being solid, although you probably know that they melt at very high temperatures. Take lead, for example. Its' melting temperature is not too high compared to other metals: around 330°C. But if we continue increasing its' temperature, just as with water, it will reach its' boiling point at around 1700°C and evaporate. It might be unusual to think about a gas of metal, but it is what actually happens to it at high temperatures.

Another example we could look at is nitrogen. Nitrogen comprises the most of atmospheric air and we are very much used to thinking of it as a gas. However, you may know (or, by now, guess) that at very low temperatures nitrogen condenses. To be precise, it happens at $-196°C = 77$ K (Kelvin scale is more convenient for low temperatures as it allows to better feel how close the temperature is to the absolute zero). If we continue lowering its temperature, nitrogen will freeze at $-210°C = 63$ K.

Our above discussion provided us with several examples of phase transitions: processes in which the state of some substance changes. Along the lines we introduced the names of phase transitions: when solid becomes liquid it is called **melting**. The reverse process when liquid becomes a solid is called **freezing**. Melting and freezing happen at the same temperature, called the melting temperature. When liquid becomes gas it is called **boiling** and the reverse process is **condensation**. Once again, boiling and condensation happen at the same temperature, called the boiling temperature.

Let us explain from the point of view of atoms and molecules why changing temperature leads to a phase transition. When we classified states of matter with respect to the interaction strength between atoms and molecules, we noted that in solids interaction is the strongest and in gases it is the weakest. However we did not specify to what do we compare this interaction strength. What we should really do is compare the interaction energy to kinetic energy of atoms and molecules, which is directly related to temperature. If kinetic energy is small compared to the interaction energy, atoms and molecules are ordered like in a crystal and don't move far from their equilibrium positions. When we increase temperature and hence increase internal kinetic energy, they atoms and molecules eventually become free to move around but not far from other atoms and molecules. This is when melting happens and after that our substance is a liquid. And if we keep increasing temperature, at some moment atoms and molecules do not have to stay near each other anymore and just start flying off randomly. The liquid has become a gas. In a gas kinetic energy of atoms and molecules is much larger than interaction energy between them.

Latent heat of melting and evaporation. As we learned last time, if we increase the temperature of some substance its' internal energy also increases. The change in internal energy is proportional to the mass of the substance, temperature increase and specific heat. Today we discuss phase transitions in which structure of a substance changes. Its internal energy also changes then - now not due to temperature increase but due to structural change. So if we take ice at 0°C and want to melt it, we need to supply some energy even though right after melting the resulting liquid water will still have the same temperature - 0°C. So, there is a change in internal energy during a phase transition which is not related to temperature change.

This change in internal energy is proportional to the mass of a substance which undergoes phase transition. Melting 2 kg of ice requires twice the energy needed to melt 1 kg of ice. The general formula for change in internal energy ΔE_{melt} during melting of a substance of mass m is:

$$\Delta E_{melt} = \lambda m.$$

The coefficient λ here is called latent heat of melting and is different for different substances. The larger it is, the more energy is needed to melt an object of the same mass. We see that during melting internal energy of a substance increases.

Conversely, during freezing internal energy of a substance decreases by exactly the same amount:

$$\Delta E_{freeze} = -\lambda m.$$

The coefficient λ here is exactly the same as for melting. So if we melt a substance and then freeze it back its' internal energy would not change.

The same ideas work for evaporation and condensation. Change of internal energy ΔE_{evap} during evaporation of a substance of mass m is

$$\Delta E_{evap} = rm.$$

where r is known as latent heat of evaporation which is different for different substances. Internal energy increases during evaporation. Conversely, during condensation internal energy decreases:

$$\Delta E_{condens} = -rm.$$

Homework

1. In what states are the following substances at room temperature: water, sugar, air, tin, alcohol, ice, oxygen, aluminum, milk, nitrogen? Make your answer in a form of a table with three columns corresponding to three basic states of matter.

2. Do the water molecules change when the water evaporates? How does the character of their motion change after evaporation?

3. 1 kg of water is mixed with some amount of ice in a thermally insulated glass. Initial temperature of the water is 10°C and initial temperature of the ice is 0°C. After coming to thermal equilibrium all of the ice melts and the resulting water has temperature exactly 0°C. How much ice (in kilograms) was initially in the glass? Specific heat of water is 4200 J/(kg·K), latent heat of melting of ice is 334 kJ/kg.

***4.** $m = 1$ kg of ice is placed into an electric kettle that has power $P = 1500$ W (which means it produces 1500 J of energy every second). Initial temperature of ice is 0°C. How much time is needed to evaporate all the water, starting with ice? The latent heat of melting and evaporation of water is 334 kJ/kg and $2,260$ kJ/kg, respectively. Specific heat of water is 4200 J/(kg·K).