

PHYS430 - Thermal Physics

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Chapter 1

Energy in Thermal Physics

1.1 Thermal Equilibrium

- After two objects have been in contact long enough, we say that they are in **thermal equilibrium**.
- The time required for a system to come to thermal equilibrium is called the **relaxation time**.
- **Temperature** is a measure of the tendency of an object to spontaneously give up energy to its surroundings.
- The flow of energy is from the object with a higher temperature to the lower one.
- For low-density gas at constant pressure, the volume should go to *zero* at approximately -273°C . which defines the **absolute zero**, in the **absolute temperature scale**, in K (kelvin).

1.2 The Ideal Gas

$$PV = nRT; \quad R = 8.31 \text{ J/mol K} \quad (1.1)$$

- A **mole** of molecules is Avogadro's number of them, 6.02×10^{23} .
- Number of molecules is $N = n \times N_A$
- Ideal gas law becomes $PV = NkT$, where k is Boltzmann's constant.
- The average transnational kinetic energy is $\bar{K}_{\text{trans}} = \frac{3}{2}kT$, where $kT = \frac{1}{40}\text{eV}$

1.3 Equipartition of Energy

Equipartition theorem At a temperature T , the average energy of any quadratic degree of freedom is $\frac{1}{2}kT$.

For a system of N molecules, each with f degree of freedom, and there are no other (non-quadratic) temperature-dependent forms of energy, then its **total thermal energy** is

$$U = Nf\frac{1}{2}kT \quad (1.2)$$

Note, This is the *average* total thermal energy, but for large N , fluctuations become negligible.

1.4 Heat and Work

- Total amount of energy in the universe never changes, **Conservation of energy**
- **Heat** any spontaneous flow of energy from one object to another, caused by difference in temperature.
- **Work**, in thermodynamics, is any other transfer of energy into or out of a system.
- Work and heat refer to energy *in transit*.
- The total energy in a system is determined, but not the work nor the heat, it's meaningless.
- We ask about how much heat *entered* a system and how much work *was done on* a system.
- $\Delta U = Q + W$ is just a statement of the law of conservation of energy, but it's still called **first law of thermodynamics**.
- Processes of heat transfer: Conduction, Convection, and Radiation.

1.5 Compression Work

- From classical mechanics work is $W = \vec{F} \cdot d\vec{r}$
- Consider compressing gas with a piston of area A a distance Δx , the change in volume is $\Delta V = -A\Delta x$
- Volume change should be quasistatic, meaning very slow so that the pressure defined is uniform. then $W = P\Delta V$, but $\Delta x = -\Delta V/A$; minus since the volume decreases.
- $W = -P\Delta V$ - quasistatic.
- If P is not constant,

$$W = - \int_{V_i}^{V_f} P(V) dV \quad (1.3)$$

- **isothermal compression** is slow that the temperature doesn't raise.
- **adiabatic compression** is so fast that no heat escapes from the gas.
- Isothermal process

- the change will be along an **isotherm** line, with $P = NkT/V$.
- The work done is

$$W = - \int_{V_i}^{V_f} P(V) dV = NkT \ln \frac{V_i}{V_f} \quad (1.4)$$

- The heat enters the system, from the first law, is

$$Q = \Delta U - W = \underbrace{\Delta \left(\frac{1}{2} N f k T \right)}_0 - W = NkT \ln \frac{V_f}{V_i} \quad (1.5)$$

- adiabatic process

- In the PV plot the change is from one isotherm to another.
- There should be no transfer of heat so

$$\Delta U = Q + W = W \quad (1.6)$$

- If it's *ideal* gas, U is proportional to T , so the temperature increases.
- By the equipartition theorem $U = \frac{f}{2}NkT$, so $dU = \frac{f}{2}Nk dT$, then from (1.3)

$$\frac{f}{2}Nk dT = -P dV \quad (1.7)$$

Using the ideal gas law for P and integrate

$$\frac{f}{2} \ln \frac{T_f}{T_i} = -\frac{V_f}{V_i} \quad \text{or} \quad V_f T_f^{f/2} = V_i T_i^{f/2} = \text{const.} \quad (1.8)$$

- Using the ideal gas law to eliminate T , $V^\gamma P = \text{const.}$, γ is the **adiabatic exponent**.

1.6 Heat Capacities

- **Heat capacity** of an object is the amount of heat needed to raise its temperature, per degree change

$$C = \frac{Q}{\Delta T} \quad (1.9)$$

- The more matter you have the larger the heat capacity, by factoring out the mass m we get **specific heat**

$$c \equiv \frac{C}{m} \quad (1.10)$$

- Note (1.10) is ambiguous, plug in the first law

$$C = \frac{Q}{\Delta T} = \frac{\Delta U - W}{\Delta T} \quad (1.11)$$

Even if the energy of an object is a well-defined function of its temperature alone, the work W done on the object is not; it depends on the process path on PV plot.

- From (1.11) The **heat capacity at constant volume**, denoted C_V

$$C_V = \left(\frac{\Delta U}{\Delta T} \right)_V = \left(\frac{\partial U}{\partial T} \right)_V \quad (1.12)$$

- From (1.11) and (1.3) the **heat capacity at constant pressure**, denoted C_P

$$C_P = \left(\frac{\Delta U - (-P\Delta V)}{\Delta T} \right)_P = \left(\frac{\partial U}{\partial T} \right)_P + P \left(\frac{\partial V}{\partial T} \right)_P \quad (1.13)$$

for solid last term is almost negligible.

- At a **phase transformation**, you add heat in a system without increasing its temperature; such as melting or boiling water. Then $C = \frac{Q}{\Delta T} = \infty$
- The amount of heat needed to do this phase transformation is called **latent heat** L , and the **specific latent heat** is

$$l \equiv \frac{L}{m} = \frac{Q}{m} \quad (1.14)$$

It's ambiguous, but we assume the pressure is constant, and no other work done.

- Adding PV onto the energy gives the **enthalpy**

$$H = U + PV \quad (1.15)$$

it's the *total* energy you would need to create the system out of nothing.

Chapter 2

The Second Law

2.1 Two-State system

- Irreversible processes are not *inevitable*, they are just overwhelmingly *probable*.
- A **microstate** is an outcome.
- A **macrostate** is saying number of particle for each state, e.g., two heads.
- **multiplicity** of a macrostate is the number of microstates for a given macrostate.
- Total multiplicity of all macrostates is the total number of microstates. Then the probability of a macrostate is

$$p = \frac{\Omega(n)}{\Omega(\text{all})} \quad (2.1)$$

- Number of different ways of choosing n items out of N , or the *combination* of n chosen from N .

$$\Omega(N, n) = \frac{N!}{n!(N-n)!} = \binom{N}{n} \quad (2.2)$$

2.2 The Einstein Model of a Solid

Consider a collection of microscopic system that can each store any number of energy ‘units’ Equal-size energy units as in quantum harmonic oscillator.

- In three-dimensional solid, each atom can oscillate in three independent directions, for N oscillators there are $N/3$ atoms.
- The multiplicity of an Einstein solid with N oscillators and q energy units is

$$\Omega(N, q) = \binom{q + N - 1}{q} = \frac{(q + N - 1)!}{q!(N - 1)!} \quad (2.3)$$

2.3 Interacting Systems

To understand the heat flow and irreversible processes, consider two Einstein solids that can share energy back and forth

- Assume the two solids are **weakly coupled**; the exchange of energy between them is slower than the exchange of energy among atoms within each solid.
- Then the individual energies of solids, U_A and U_B , will change slowly; over short time they are fixed.
- On longer time scales the values of U_A and U_B will change, so we consider $U_{\text{total}} = U_A + U_B$.
- The total multiplicity for independent system is just the product of Ω_A and Ω_B .
- **Fundamental assumption of statistical mechanics** In an isolated system in thermal equilibrium, all accessible microstates are equally probable.
- Invoking this principle on the two Einstein solids, we conclude that, while all the *microstates* are equally probable, some *macrostates* are more probable than others.
- The *heat*, then, is a probabilistic phenomenon; if system started *initially* with all the energy in solid B and wait for a while, it's more certain to find that the energy has flowed from B to A .
- The tendency of increasing multiplicity is the **second law of thermodynamics**.

2.4 Large Systems

- There are three categories of numbers here:
 - **small numbers**, 12, 43
 - **large numbers**, in order of Avogadro's number 10^{23}
 - **very large numbers**, exponentiating of large numbers.
- Adding a small number to a large number doesn't change. Multiplying a large number by a very large number.
- Using Stirling's approximation for factorial of a large number

$$N! \approx N^N e^{-N} \sqrt{2\pi N}; \quad N \gg 1 \quad (2.4)$$

- The approximated multiplicity is

$$\Omega(N, q) \approx \left(\frac{eq}{N}\right)^N; \quad q \gg N \quad (2.5)$$

within the high-temperature limit.

- Multiplicity of two Einstein interacting solids with N oscillators and total q energy units is

$$\Omega = \left(\frac{eq_A}{N}\right)^N \left(\frac{eq_B}{N}\right)^N = \left(\frac{e}{N}\right)^{2N} (q_A q_B)^N \quad (2.6)$$

- Taking $\Omega = \Omega(q_A)$, it has a peak at $q_A = q/2$ with a very large number value of

$$\Omega_{\text{max}} = \left(\frac{e}{N}\right)^{2N} \left(\frac{q}{2}\right)^{2N} \quad (2.7)$$

- Around this maximum, Ω is a **Gaussian** as

$$\Omega = \Omega_{\max} e^{-N(2x/q)^2} \quad (2.8)$$

- $\Omega = \Omega_{\max}/e$ when

$$x = \frac{q}{2\sqrt{N}}$$

the width is q/\sqrt{N}

2.5 The Ideal Gas

- For ideal gas the states are proportional to the ‘volume’ of available **momentum space**.

$$\Omega_1 \propto V \cdot V_p$$

- To have a finite number of microstates we invoke quantum mechanics principles of wavefunction, which is spread in both position and momentum spaces; it adheres to the *Heidenberg*
- The molecule’s kinetic energy equals U ,

$$U = \frac{1}{2}m(v_x^2 + v_y^2 + v_z^2) = \frac{1}{2m}(p_x^2 + p_y^2 + p_z^2) \quad \text{or} \quad p_x^2 + p_y^2 + p_z^2 = 2mU \quad (2.9)$$

which is the surface of a *sphere* in momentum space with radius $\sqrt{2mU}$

- Multiplicity of an ideal gas of two *distinguishable* molecules is

$$\Omega_2 = \frac{V^2}{h^6} A \quad (2.10)$$

Where A is area of momentum hypersphere.

- Multiplicity of an ideal gas of two *indistinguishable* is less by a factor of 2

$$\Omega_2 = \frac{1}{2} \frac{V^2}{h^6} A \quad (2.11)$$

- For an ideal gas of N indistinguishable molecules

$$\Omega_N = \frac{1}{N!} \frac{V^N}{h^{3N}} \times A \quad (2.12)$$

where A is surface area of a $3N$ -dimensional hypersphere whose radius $\sqrt{2mU}$.

- Surface area of hypersphere in d -dimensional is

$$A = \frac{2\pi^{d/2}}{(\frac{d}{2} - 1)!} r^{d-1} \quad (2.13)$$

- Then, having that $d = 3N$ and $r = \sqrt{2mU}$, for monoatomic gas

$$\Omega_N = \frac{1}{N!} \frac{V^N}{h^{3N}} \frac{2\pi^{3N/2}}{(\frac{3N}{2} - 1)!} (\sqrt{2mU})^{3N-1} \approx \frac{1}{N!} \frac{V^N}{h^{3N}} \frac{2\pi^{3N/2}}{(\frac{3N}{2})!} (\sqrt{2mU})^{3N} \quad (2.14)$$

or to simplify the formula where, $f(N)$ is function of N

$$\Omega(U, V, N) = f(N) V^N U^{3N/2} \quad (2.15)$$

- Suppose *two* ideal gases separated by a partition that allows energy to flow, and if each gas has N molecules, the total multiplicity is

$$\Omega_{\text{total}} = [f(N)]^2 (V_A V_B)^N (U_A U_B)^{3N/2} \quad (2.16)$$

with a peak-width of $\frac{U_{\text{total}}}{\sqrt{3N/2}}$

- Now allow gases to exchange volume with a movable partition, we'll have a width-peak of $\frac{V_{\text{total}}}{\sqrt{3N/2}}$

2.6 Entropy

- Any large systems in equilibrium will be found in the macrostate with the greatest multiplicity, a general statement for the **second law of thermodynamics**
- Or multiplicity tends to increase.
- To simplify dealing with very large number of Ω , we define the **entropy** as

$$S \equiv k \ln \Omega \quad [\text{J/K}] \quad (2.17)$$

- Entropy tends to increase.
- No matter what you do to decrease the entropy in one place, you're bound to create at least as much entropy somewhere else.
- Entropy for idea gas, with Stirling's approximation, is called **Sackur-Tetrode equation**

$$S = Nk \left[\ln \left(\frac{V}{N} \left(\frac{4\pi m U}{3N h^2} \right)^{3/2} \right) + \frac{5}{2} \right] \quad (2.18)$$

- Entropy of an ideal gas depends on its volume, energy, and number of particles.
- If the volume changes from V_i to V_f

$$\Delta S = Nk \ln \frac{V_f}{V_i} \quad (U, N \text{ fixed}) \quad (2.19)$$

- In **free expansion** no work is done by gas nor heat $\Delta U = Q + W = 0 + 0 = 0$, however there's an increase in entropy by (2.19)
- Suppose two different monoatomic idea gases, A and B , each with the same energy, volume and of particles. After mixing them, each gas will expand to twice its initial volume, so $\Delta S_A = Nk \ln 2$, then the total entropy is **Entropy of mixing** $\Delta S_{\text{total}} = 2Nk \ln 2$