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# Chapter 4

## Statistical Ensembles

### 4.1 References

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This has been perhaps the most popular undergraduate text since it first appeared in 1967, and with good reason.
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A very relaxed treatment appropriate for undergraduate physics majors.
- D. V. Schroeder, *An Introduction to Thermal Physics* (Addison-Wesley, 2000)  
This is the best undergraduate thermodynamics book I've come across, but only 40% of the book treats statistical mechanics.
- C. Kittel, *Elementary Statistical Physics* (Dover, 2004)  
Remarkably crisp, though dated, this text is organized as a series of brief discussions of key concepts and examples. Published by Dover, so you can't beat the price.
- M. Kardar, *Statistical Physics of Particles* (Cambridge, 2007)  
A superb modern text, with many insightful presentations of key concepts.
- M. Plischke and B. Bergersen, *Equilibrium Statistical Physics* (3<sup>rd</sup> edition, World Scientific, 2006)  
An excellent graduate level text. Less insightful than Kardar but still a good modern treatment of the subject. Good discussion of mean field theory.
- E. M. Lifshitz and L. P. Pitaevskii, *Statistical Physics* (part I, 3<sup>rd</sup> edition, Pergamon, 1980)  
This is volume 5 in the famous Landau and Lifshitz *Course of Theoretical Physics*. Though dated, it still contains a wealth of information and physical insight.

## 4.2 Microcanonical Ensemble ( $\mu$ CE)

### 4.2.1 The microcanonical distribution function

We have seen how in an *ergodic* dynamical system, time averages can be replaced by phase space averages:

$$\text{ergodicity} \iff \langle f(\varphi) \rangle_t = \langle f(\varphi) \rangle_S, \quad (4.1)$$

where

$$\langle f(\varphi) \rangle_t = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T dt f(\varphi(t)). \quad (4.2)$$

and

$$\langle f(\varphi) \rangle_S = \int d\mu f(\varphi) \delta(E - \hat{H}(\varphi)) / \int d\mu \delta(E - \hat{H}(\varphi)). \quad (4.3)$$

Here  $\hat{H}(\varphi) = \hat{H}(\mathbf{q}, \mathbf{p})$  is the Hamiltonian, and where  $\delta(x)$  is the Dirac  $\delta$ -function<sup>1</sup>. Thus, averages are taken over a constant energy hypersurface which is a subset of the entire phase space.

We've also seen how any phase space distribution  $\varrho(\Lambda_1, \dots, \Lambda_k)$  which is a function of conserved quantities  $\Lambda_a(\varphi)$  is automatically a stationary (time-independent) solution to Liouville's equation. Note that the microcanonical distribution,

$$\varrho_E(\varphi) = \delta(E - \hat{H}(\varphi)) / \int d\mu \delta(E - \hat{H}(\varphi)), \quad (4.4)$$

is of this form, since  $\hat{H}(\varphi)$  is conserved by the dynamics. Linear and angular momentum conservation generally are broken by elastic scattering off the walls of the sample.

So averages in the microcanonical ensemble are computed by evaluating the ratio

$$\langle A \rangle = \frac{\text{Tr} A \delta(E - \hat{H})}{\text{Tr} \delta(E - \hat{H})}, \quad (4.5)$$

where Tr means 'trace', which entails an integration over all phase space:

$$\text{Tr} A(q, p) \equiv \frac{1}{N!} \prod_{i=1}^N \int \frac{d^d p_i d^d q_i}{(2\pi\hbar)^d} A(q, p). \quad (4.6)$$

Here  $N$  is the total number of particles and  $d$  is the dimension of physical space in which each particle moves. The factor of  $1/N!$ , which cancels in the ratio between numerator and denominator, is present for *indistinguishable particles*. The normalization factor  $(2\pi\hbar)^{-Nd}$  renders the trace dimensionless. Again, this cancels between numerator and denominator. These factors may then seem arbitrary in the definition of the trace, but we'll see how they in fact are required from quantum mechanical considerations. So we now adopt the following metric for classical phase space integration:

$$d\mu = \frac{1}{N!} \prod_{i=1}^N \frac{d^d p_i d^d q_i}{(2\pi\hbar)^d}. \quad (4.7)$$

<sup>1</sup>We write the Hamiltonian as  $\hat{H}$  (classical or quantum) in order to distinguish it from magnetic field ( $H$ ) or enthalpy ( $H$ ).

### 4.2.2 Density of states

The denominator,

$$D(E) = \text{Tr } \delta(E - \hat{H}) , \quad (4.8)$$

is called the *density of states*. It has dimensions of inverse energy, such that

$$\begin{aligned} D(E) \Delta E &= \int_E^{E+\Delta E} dE' \int d\mu \delta(E' - \hat{H}) = \int_{E < \hat{H} < E+\Delta E} d\mu \\ &= \# \text{ of states with energies between } E \text{ and } E + \Delta E . \end{aligned} \quad (4.9)$$

Let us now compute  $D(E)$  for the nonrelativistic ideal gas. The Hamiltonian is

$$\hat{H}(q, p) = \sum_{i=1}^N \frac{\mathbf{p}_i^2}{2m} . \quad (4.10)$$

We assume that the gas is enclosed in a region of volume  $V$ , and we'll do a purely classical calculation, neglecting discreteness of its quantum spectrum. We must compute

$$D(E) = \frac{1}{N!} \int \prod_{i=1}^N \frac{d^d p_i d^d q_i}{(2\pi\hbar)^d} \delta\left(E - \sum_{i=1}^N \frac{\mathbf{p}_i^2}{2m}\right) . \quad (4.11)$$

We'll do this calculation in two ways. First, let's rescale  $p_i^\alpha \equiv \sqrt{2mE} u_i^\alpha$ . We then have

$$D(E) = \frac{V^N}{N!} \left(\frac{\sqrt{2mE}}{h}\right)^{Nd} \frac{1}{E} \int d^M u \delta(u_1^2 + u_2^2 + \dots + u_M^2 - 1) . \quad (4.12)$$

Here we have written  $\mathbf{u} = (u_1, u_2, \dots, u_M)$  with  $M = Nd$  as a  $M$ -dimensional vector. We've also used the rule  $\delta(E/x) = E^{-1}\delta(x)$  for  $\delta$ -functions. We can now write

$$d^M u = u^{M-1} du d\Omega_M , \quad (4.13)$$

where  $d\Omega_M$  is the  $M$ -dimensional differential solid angle. We now have our answer:<sup>2</sup>

$$D(E) = \frac{V^N}{N!} \left(\frac{\sqrt{2m}}{h}\right)^{Nd} E^{\frac{1}{2}Nd-1} \cdot \frac{1}{2} \Omega_{Nd} . \quad (4.14)$$

What remains is for us to compute  $\Omega_M$ , the total solid angle in  $M$  dimensions. We do this by a nifty mathematical trick. Consider the integral

$$\begin{aligned} \mathcal{I}_M &= \int d^M u e^{-u^2} = \Omega_M \int_0^\infty du u^{M-1} e^{-u^2} \\ &= \frac{1}{2} \Omega_M \int_0^\infty ds s^{\frac{1}{2}M-1} e^{-s} = \frac{1}{2} \Omega_M \Gamma\left(\frac{1}{2}M\right) , \end{aligned} \quad (4.15)$$

<sup>2</sup>The factor of  $\frac{1}{2}$  preceding  $\Omega_M$  in eqn. 4.14 appears because  $\delta(u^2 - 1) = \frac{1}{2} \delta(u - 1) + \frac{1}{2} \delta(u + 1)$ . Since  $u = |\mathbf{u}| \geq 0$ , the second term can be dropped.

where  $s = u^2$ , and where

$$\Gamma(z) = \int_0^{\infty} dt t^{z-1} e^{-t} \quad (4.16)$$

is the Gamma function, which satisfies  $z \Gamma(z) = \Gamma(z + 1)$ .<sup>3</sup> On the other hand, we can compute  $\mathcal{I}_M$  in Cartesian coordinates, writing

$$\mathcal{I}_M = \left( \int_{-\infty}^{\infty} du_1 e^{-u_1^2} \right)^M = (\sqrt{\pi})^M. \quad (4.17)$$

Therefore

$$\Omega_M = \frac{2\pi^{M/2}}{\Gamma(M/2)}. \quad (4.18)$$

We thereby obtain  $\Omega_2 = 2\pi$ ,  $\Omega_3 = 4\pi$ ,  $\Omega_4 = 2\pi^2$ , etc., the first two of which are familiar.

Our final result, then, is

$$D(E, V, N) = \frac{V^N}{N!} \left( \frac{m}{2\pi\hbar^2} \right)^{Nd/2} \frac{E^{\frac{1}{2}Nd-1}}{\Gamma(Nd/2)}. \quad (4.19)$$

Here we have emphasized that the density of states is a function of  $E$ ,  $V$ , and  $N$ . Using Stirling's approximation,

$$\ln N! = N \ln N - N + \frac{1}{2} \ln N + \frac{1}{2} \ln(2\pi) + \mathcal{O}(N^{-1}), \quad (4.20)$$

we may define the *statistical entropy*,

$$S(E, V, N) \equiv k_B \ln D(E, V, N) = N k_B \phi \left( \frac{E}{N}, \frac{V}{N} \right) + \mathcal{O}(\ln N), \quad (4.21)$$

where

$$\phi \left( \frac{E}{N}, \frac{V}{N} \right) = \frac{d}{2} \ln \left( \frac{E}{N} \right) + \ln \left( \frac{V}{N} \right) + \frac{d}{2} \ln \left( \frac{m}{d\pi\hbar^2} \right) + \left( 1 + \frac{1}{2}d \right). \quad (4.22)$$

Recall  $k_B = 1.3806503 \times 10^{-16}$  erg/K is Boltzmann's constant.

The second way to calculate  $D(E)$  is to first compute its *Laplace transform*,  $Z(\beta)$ :

$$Z(\beta) = \mathcal{L}[D(E)] \equiv \int_0^{\infty} dE e^{-\beta E} D(E) = \text{Tr} e^{-\beta \hat{H}}. \quad (4.23)$$

The inverse Laplace transform is then

$$D(E) = \mathcal{L}^{-1}[Z(\beta)] \equiv \int_{c-i\infty}^{c+i\infty} \frac{d\beta}{2\pi i} e^{\beta E} Z(\beta), \quad (4.24)$$

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<sup>3</sup>Note that for integer argument,  $\Gamma(k) = (k-1)!$



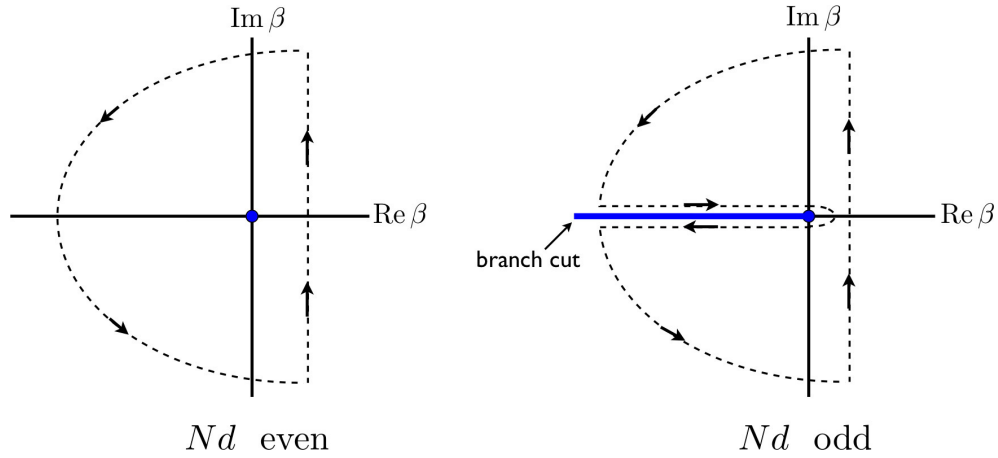


Figure 4.1: Complex integration contours  $\mathcal{C}$  for inverse Laplace transform  $\mathcal{L}^{-1}[Z(\beta)] = D(E)$ . When the product  $dN$  is odd, there is a branch cut along the negative  $\text{Re } \beta$  axis.

where  $c$  is such that the integration contour is to the right of any singularities of  $Z(\beta)$  in the complex  $\beta$ -plane. We then have

$$\begin{aligned}
 Z(\beta) &= \frac{1}{N!} \prod_{i=1}^N \int \frac{d^d x_i d^d p_i}{(2\pi\hbar)^d} e^{-\beta p_i^2/2m} \\
 &= \frac{V^N}{N!} \left( \int_{-\infty}^{\infty} \frac{dp}{2\pi\hbar} e^{-\beta p^2/2m} \right)^{Nd} \\
 &= \frac{V^N}{N!} \left( \frac{m}{2\pi\hbar^2} \right)^{Nd/2} \beta^{-Nd/2}.
 \end{aligned} \tag{4.25}$$

The inverse Laplace transform is then

$$\begin{aligned}
 D(E) &= \frac{V^N}{N!} \left( \frac{m}{2\pi\hbar^2} \right)^{Nd/2} \oint_{\mathcal{C}} \frac{d\beta}{2\pi i} e^{\beta E} \beta^{-Nd/2} \\
 &= \frac{V^N}{N!} \left( \frac{m}{2\pi\hbar^2} \right)^{Nd/2} \frac{E^{\frac{1}{2}Nd-1}}{\Gamma(Nd/2)},
 \end{aligned} \tag{4.26}$$

exactly as before. The integration contour for the inverse Laplace transform is extended in an infinite semicircle in the left half  $\beta$ -plane. When  $Nd$  is even, the function  $\beta^{-Nd/2}$  has a simple pole of order  $Nd/2$  at the origin. When  $Nd$  is odd, there is a branch cut extending along the negative  $\text{Re } \beta$  axis, and the integration contour must avoid the cut, as shown in fig. 4.1.

For a general system, the Laplace transform,  $Z(\beta) = \mathcal{L}[D(E)]$  also is called the *partition function*. We shall again meet up with  $Z(\beta)$  when we discuss the ordinary canonical ensemble.

### 4.2.3 Arbitrariness in the definition of $S(E)$

Note that  $D(E)$  has dimensions of inverse energy, so one might ask how we are to take the logarithm of a dimensionful quantity in eqn. 4.21. We must introduce an energy scale, such as  $\Delta E$  in eqn. 4.9, and define  $\tilde{D}(E; \Delta E) = D(E) \Delta E$  and  $S(E; \Delta E) \equiv k_B \ln \tilde{D}(E; \Delta E)$ . The definition of statistical entropy then involves the arbitrary parameter  $\Delta E$ , however this only affects  $S(E)$  in an additive way. That is,

$$S(E, V, N; \Delta E_1) = S(E, V, N; \Delta E_2) + k_B \ln \left( \frac{\Delta E_1}{\Delta E_2} \right). \quad (4.27)$$

Note that the difference between the two definitions of  $S$  depends only on the ratio  $\Delta E_1/\Delta E_2$ , and is independent of  $E, V$ , and  $N$ .

### 4.2.4 Ultra-relativistic ideal gas

Consider an ultrarelativistic ideal gas, with single particle dispersion  $\varepsilon(p) = cp$ . We then have

$$\begin{aligned} Z(\beta) &= \frac{V^N}{N!} \frac{\Omega_d^N}{h^{Nd}} \left( \int_0^\infty dp p^{d-1} e^{-\beta cp} \right)^N \\ &= \frac{V^N}{N!} \left( \frac{\Gamma(d) \Omega_d}{c^d h^d \beta^d} \right)^N. \end{aligned} \quad (4.28)$$

The statistical entropy is  $S(E, V, N) = k_B \ln D(E, V, N) = N k_B \phi\left(\frac{E}{N}, \frac{V}{N}\right)$ , with

$$\phi\left(\frac{E}{N}, \frac{V}{N}\right) = d \ln\left(\frac{E}{N}\right) + \ln\left(\frac{V}{N}\right) + \ln\left(\frac{\Omega_d \Gamma(d)}{(dhc)^d}\right) + (d+1) \quad (4.29)$$

### 4.2.5 Discrete systems

For classical systems where the energy levels are discrete, the states of the system  $|\sigma\rangle$  are labeled by a set of discrete quantities  $\{\sigma_1, \sigma_2, \dots\}$ , where each variable  $\sigma_i$  takes discrete values. The number of ways of configuring the system at fixed energy  $E$  is then

$$\Omega(E, N) = \sum_{\sigma} \delta_{\hat{H}(\sigma), E}, \quad (4.30)$$

where the sum is over all possible configurations. Here  $N$  labels the total number of particles. For example, if we have  $N$  spin- $\frac{1}{2}$  particles on a lattice which are placed in a magnetic field  $H$ , so the individual particle energy is  $\varepsilon_i = -\mu_0 H \sigma$ , where  $\sigma = \pm 1$ , then in a configuration in which  $N_\uparrow$  particles have  $\sigma_i = +1$  and  $N_\downarrow = N - N_\uparrow$  particles have  $\sigma_i = -1$ , the energy is  $E = (N_\downarrow - N_\uparrow)\mu_0 H$ . The number of configurations at fixed energy  $E$  is

$$\Omega(E, N) = \binom{N}{N_\uparrow} = \frac{N!}{\left(\frac{N}{2} - \frac{E}{2\mu_0 H}\right)! \left(\frac{N}{2} + \frac{E}{2\mu_0 H}\right)!}, \quad (4.31)$$

since  $N_{\uparrow/\downarrow} = \frac{N}{2} \mp \frac{E}{2\mu_0 H}$ . The statistical entropy is  $S(E, N) = k_B \ln \Omega(E, N)$ .

### 4.3 The Quantum Mechanical Trace

Thus far our understanding of ergodicity is rooted in the dynamics of classical mechanics. A Hamiltonian flow which is ergodic is one in which time averages can be replaced by phase space averages using the microcanonical ensemble. What happens, though, if our system is quantum mechanical, as all systems ultimately are?

#### 4.3.1 The density matrix

First, let us consider that our system  $S$  will in general be in contact with a world  $W$ . We call the union of  $S$  and  $W$  the universe,  $U = W \cup S$ . Let  $|N\rangle$  denote a quantum mechanical state of  $W$ , and let  $|n\rangle$  denote a quantum mechanical state of  $S$ . Then the most general wavefunction we can write is of the form

$$|\Psi\rangle = \sum_{N,n} \Psi_{N,n} |N\rangle \otimes |n\rangle. \quad (4.32)$$

Now let us compute the expectation value of some operator  $\hat{A}$  which acts as the identity within  $W$ , meaning  $\langle N | \hat{A} | N' \rangle = \hat{A} \delta_{NN'}$ , where  $\hat{A}$  is the 'reduced' operator which acts within  $S$  alone. We then have

$$\begin{aligned} \langle \Psi | \hat{A} | \Psi \rangle &= \sum_{N,N'} \sum_{n,n'} \Psi_{N,n}^* \Psi_{N',n'} \delta_{NN'} \langle n | \hat{A} | n' \rangle \\ &= \text{Tr}(\hat{\rho} \hat{A}), \end{aligned} \quad (4.33)$$

where

$$\hat{\rho} = \sum_N \sum_{n,n'} \Psi_{N,n}^* \Psi_{N,n'} |n'\rangle \langle n| \quad (4.34)$$

is the *density matrix*. The time-dependence of  $\hat{\rho}$  is easily found:

$$\begin{aligned} \hat{\rho}(t) &= \sum_N \sum_{n,n'} \Psi_{N,n}^* \Psi_{N,n'} |n'(t)\rangle \langle n(t)| \\ &= e^{-i\hat{H}t/\hbar} \hat{\rho} e^{+i\hat{H}t/\hbar}, \end{aligned} \quad (4.35)$$

where  $\hat{H}$  is the Hamiltonian for the system  $S$ . Thus, we find

$$i\hbar \frac{\partial \hat{\rho}}{\partial t} = [\hat{H}, \hat{\rho}]. \quad (4.36)$$

Note that the density matrix evolves according to a slightly different equation than an operator in the Heisenberg picture, for which

$$\hat{A}(t) = e^{+iHt/\hbar} A e^{-i\hat{H}t/\hbar} \quad \Longrightarrow \quad i\hbar \frac{\partial \hat{A}}{\partial t} = [\hat{A}, \hat{H}] = -[\hat{H}, \hat{A}]. \quad (4.37)$$

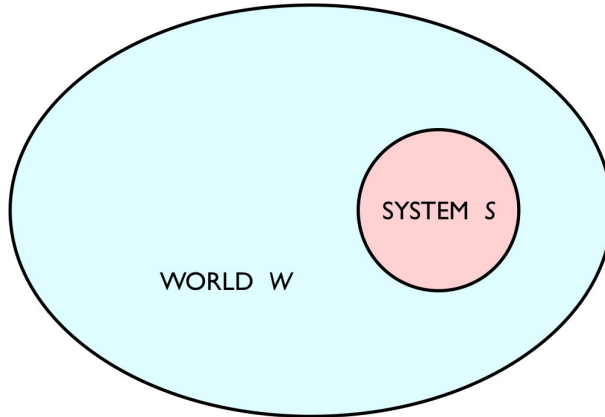


Figure 4.2: A system  $S$  in contact with a ‘world’  $W$ . The union of the two, universe  $U = W \cup S$ , is said to be the ‘universe’.

For Hamiltonian systems, we found that the phase space distribution  $\varrho(q, p, t)$  evolved according to the Liouville equation,

$$i \frac{\partial \varrho}{\partial t} = L \varrho, \quad (4.38)$$

where the Liouvillian  $L$  is the differential operator

$$L = -i \sum_{j=1}^{Nd} \left\{ \frac{\partial \hat{H}}{\partial p_j} \frac{\partial}{\partial q_j} - \frac{\partial \hat{H}}{\partial q_j} \frac{\partial}{\partial p_j} \right\}. \quad (4.39)$$

Accordingly, any distribution  $\varrho(\Lambda_1, \dots, \Lambda_k)$  which is a function of constants of the motion  $\Lambda_a(q, p)$  is a stationary solution to the Liouville equation:  $\partial_t \varrho(\Lambda_1, \dots, \Lambda_k) = 0$ . Similarly, any quantum mechanical density matrix which commutes with the Hamiltonian is a stationary solution to eqn. 4.36. The corresponding microcanonical distribution is

$$\hat{\varrho}_E = \delta(E - \hat{H}). \quad (4.40)$$

### 4.3.2 Averaging the DOS

If our quantum mechanical system is placed in a finite volume, the energy levels will be discrete, rather than continuous, and the density of states (DOS) will be of the form

$$D(E) = \text{Tr} \delta(E - \hat{H}) = \sum_l \delta(E - E_l), \quad (4.41)$$

where  $\{E_l\}$  are the eigenvalues of the Hamiltonian  $\hat{H}$ . In the thermodynamic limit,  $V \rightarrow \infty$ , and the discrete spectrum of kinetic energies remains discrete for all finite  $V$  but must approach the continuum result. To recover the continuum result, we average the DOS over a window of width  $\Delta E$ :

$$\overline{D(E)} = \frac{1}{\Delta E} \int_E^{E+\Delta E} dE' D(E'). \quad (4.42)$$

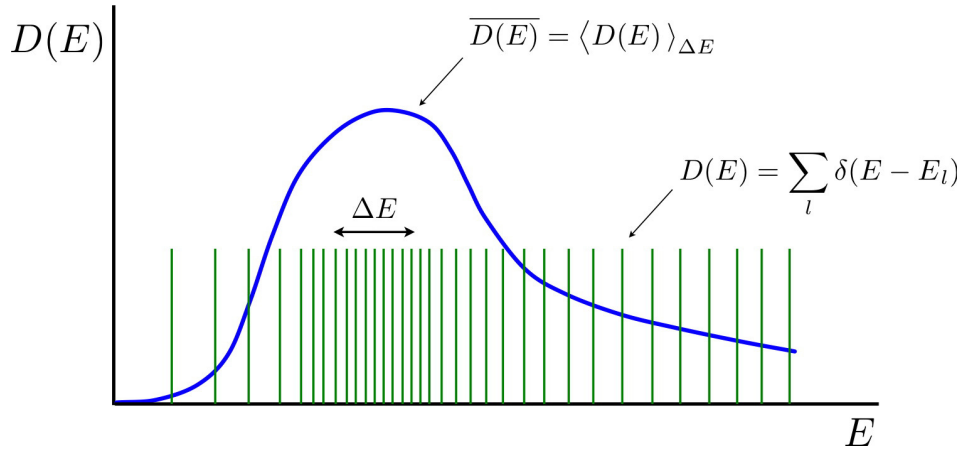


Figure 4.3: Averaging the quantum mechanical discrete density of states yields a continuous curve.

If we take the limit  $\Delta E \rightarrow 0$  but with  $\Delta E \gg \delta E$ , where  $\delta E$  is the spacing between successive quantized levels, we recover a smooth function, as shown in fig. 4.3. We will in general drop the bar and refer to this function as  $D(E)$ . Note that  $\delta E \sim 1/D(E) = e^{-N\phi(\varepsilon, v)}$  is (typically) *exponentially* small in the size of the system, hence if we took  $\Delta E \propto V^{-1}$  which vanishes in the thermodynamic limit, there are still exponentially many energy levels within an interval of width  $\Delta E$ .

### 4.3.3 Coherent states

The quantum-classical correspondence is elucidated with the use of *coherent states*. Recall that the one-dimensional harmonic oscillator Hamiltonian may be written

$$\begin{aligned} \hat{H}_0 &= \frac{p^2}{2m} + \frac{1}{2}m\omega_0^2 q^2 \\ &= \hbar\omega_0 \left( a^\dagger a + \frac{1}{2} \right), \end{aligned} \quad (4.43)$$

where  $a$  and  $a^\dagger$  are *ladder operators* satisfying  $[a, a^\dagger] = 1$ , which can be taken to be

$$a = \ell \frac{\partial}{\partial q} + \frac{q}{2\ell}, \quad a^\dagger = -\ell \frac{\partial}{\partial q} + \frac{q}{2\ell}, \quad (4.44)$$

with  $\ell = \sqrt{\hbar/2m\omega_0}$ . Note that

$$q = \ell (a + a^\dagger), \quad p = \frac{\hbar}{2i\ell} (a - a^\dagger). \quad (4.45)$$

The ground state satisfies  $a\psi_0(q) = 0$ , which yields

$$\psi_0(q) = (2\pi\ell^2)^{-1/4} e^{-q^2/4\ell^2}. \quad (4.46)$$

The normalized *coherent state*  $|z\rangle$  is defined as

$$|z\rangle = e^{-\frac{1}{2}|z|^2} e^{za^\dagger} |0\rangle = e^{-\frac{1}{2}|z|^2} \sum_{n=0}^{\infty} \frac{z^n}{\sqrt{n!}} |n\rangle. \quad (4.47)$$

The overlap of coherent states is given by

$$\langle z_1 | z_2 \rangle = e^{-\frac{1}{2}|z_1|^2} e^{-\frac{1}{2}|z_2|^2} e^{\bar{z}_1 z_2}, \quad (4.48)$$

hence different coherent states are not orthogonal. Despite this nonorthogonality, the coherent states allow a simple resolution of the identity,

$$1 = \int \frac{d^2z}{2\pi i} |z\rangle \langle z| \quad ; \quad \frac{d^2z}{2\pi i} \equiv \frac{d\text{Re}z \, d\text{Im}z}{\pi} \quad (4.49)$$

which is straightforward to establish.

To gain some physical intuition about the coherent states, define

$$z \equiv \frac{Q}{2\ell} + \frac{i\ell P}{\hbar} \quad (4.50)$$

and write  $|z\rangle \equiv |Q, P\rangle$ . One finds (*exercise!*)

$$\psi_{Q,P}(q) = \langle q | z \rangle = (2\pi\ell^2)^{-1/4} e^{-iPQ/2\hbar} e^{iPq/\hbar} e^{-(q-Q)^2/4\ell^2}, \quad (4.51)$$

hence the coherent state  $\psi_{Q,P}(q)$  is a wavepacket Gaussianly localized about  $q = Q$ , but oscillating with average momentum  $P$ .

For example, we can compute

$$\langle Q, P | q | Q, P \rangle = \langle z | \ell(a + a^\dagger) | z \rangle = 2\ell \text{Re} z = Q \quad (4.52)$$

$$\langle Q, P | p | Q, P \rangle = \langle z | \frac{\hbar}{2i\ell} (a - a^\dagger) | z \rangle = \frac{\hbar}{\ell} \text{Im} z = P \quad (4.53)$$

as well as

$$\langle Q, P | q^2 | Q, P \rangle = \langle z | \ell^2 (a + a^\dagger)^2 | z \rangle = Q^2 + \ell^2 \quad (4.54)$$

$$\langle Q, P | p^2 | Q, P \rangle = -\langle z | \frac{\hbar^2}{4\ell^2} (a - a^\dagger)^2 | z \rangle = P^2 + \frac{\hbar^2}{4\ell^2}. \quad (4.55)$$

Thus, the root mean square fluctuations in the coherent state  $|Q, P\rangle$  are

$$\Delta q = \ell = \sqrt{\frac{\hbar}{2m\omega_0}} \quad , \quad \Delta p = \frac{\hbar}{2\ell} = \sqrt{\frac{m\hbar\omega_0}{2}}, \quad (4.56)$$

and  $\Delta q \cdot \Delta p = \frac{1}{2} \hbar$ . Thus we learn that the coherent state  $\psi_{Q,P}(q)$  is localized in phase space, *i.e.* in both position and momentum. If we have a general operator  $\hat{A}(q, p)$ , we can then write

$$\langle Q, P | \hat{A}(q, p) | Q, P \rangle = A(Q, P) + \mathcal{O}(\hbar), \quad (4.57)$$

where  $A(Q, P)$  is formed from  $\hat{A}(q, p)$  by replacing  $q \rightarrow Q$  and  $p \rightarrow P$ .

Since

$$\frac{d^2z}{2\pi i} \equiv \frac{d\text{Re}z d\text{Im}z}{\pi} = \frac{dQ dP}{2\pi\hbar}, \quad (4.58)$$

we can write the trace using coherent states as

$$\text{Tr } \hat{A} = \frac{1}{2\pi\hbar} \int_{-\infty}^{\infty} dQ \int_{-\infty}^{\infty} dP \langle Q, P | \hat{A} | Q, P \rangle. \quad (4.59)$$

We now can understand the origin of the factor  $2\pi\hbar$  in the denominator of each  $(q_i, p_i)$  integral over classical phase space in eqn. 4.6.

Note that  $\omega_0$  is arbitrary in our discussion. By increasing  $\omega_0$ , the states become more localized in  $q$  and more plane wave like in  $p$ . However, so long as  $\omega_0$  is finite, the width of the coherent state in each direction is proportional to  $\hbar^{1/2}$ , and thus vanishes in the classical limit.

## 4.4 Thermal Equilibrium

### 4.4.1 Two systems in thermal contact

Consider two systems in thermal contact, as depicted in fig. 4.4. The two subsystems #1 and #2 are free to exchange energy, but their respective volumes and particle numbers remain fixed. We assume the contact is made over a surface, and that the energy associated with that surface is negligible when compared with the bulk energies  $E_1$  and  $E_2$ . Let the total energy be  $E = E_1 + E_2$ . Then the density of states  $D(E)$  for the combined system is

$$D(E) = \int dE_1 D_1(E_1) D_2(E - E_1). \quad (4.60)$$

The probability density for system #1 to have energy  $E_1$  is then

$$P_1(E_1) = \frac{D_1(E_1) D_2(E - E_1)}{D(E)}. \quad (4.61)$$

Note that  $P_1(E_1)$  is normalized:  $\int dE_1 P_1(E_1) = 1$ . We now ask: what is the most probable value of  $E_1$ ? We find out by differentiating  $P_1(E_1)$  with respect to  $E_1$  and setting the result to zero. This requires

$$\begin{aligned} 0 &= \frac{1}{P_1(E_1)} \frac{dP_1(E_1)}{dE_1} = \frac{\partial}{\partial E_1} \ln P_1(E_1) \\ &= \frac{\partial}{\partial E_1} \ln D_1(E_1) + \frac{\partial}{\partial E_1} \ln D_2(E - E_1). \end{aligned} \quad (4.62)$$

We conclude that the maximally likely partition of energy between systems #1 and #2 is realized when

$$\frac{\partial S_1}{\partial E_1} = \frac{\partial S_2}{\partial E_2}. \quad (4.63)$$

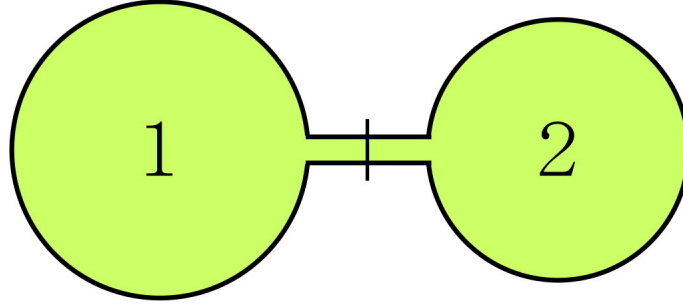


Figure 4.4: Two systems in thermal contact.

This guarantees that

$$S(E, E_1) = S_1(E_1) + S_2(E - E_1) \quad (4.64)$$

is a maximum with respect to the energy  $E_1$ , at fixed total energy  $E$ .

The *temperature*  $T$  is defined as

$$\frac{1}{T} = \left( \frac{\partial S}{\partial E} \right)_{V, N}, \quad (4.65)$$

a result familiar from thermodynamics. The difference is now we have a more rigorous definition of the entropy. When the total entropy  $S$  is maximized, we have that  $T_1 = T_2$ . Once again, two systems in thermal contact and can exchange energy will in equilibrium have equal temperatures.

According to eqns. 4.22 and 4.29, the entropies of nonrelativistic and ultrarelativistic ideal gases in  $d$  space dimensions are given by

$$S_{\text{NR}} = \frac{1}{2} N d k_B \ln \left( \frac{E}{N} \right) + N k_B \ln \left( \frac{V}{N} \right) + \text{const.} \quad (4.66)$$

$$S_{\text{UR}} = N d k_B \ln \left( \frac{E}{N} \right) + N k_B \ln \left( \frac{V}{N} \right) + \text{const.} \quad (4.67)$$

Invoking eqn. 4.65, we then have

$$E_{\text{NR}} = \frac{1}{2} N d k_B T, \quad E_{\text{UR}} = N d k_B T. \quad (4.68)$$

We saw that the probability distribution  $P_1(E_1)$  is maximized when  $T_1 = T_2$ , but how sharp is the peak in the distribution? Let us write  $E_1 = E_1^* + \Delta E_1$ , where  $E_1^*$  is the solution to eqn. 4.62. We then have

$$\ln P_1(E_1^* + \Delta E_1) = \ln P_1(E_1^*) + \frac{1}{2k_B} \left. \frac{\partial^2 S_1}{\partial E_1^2} \right|_{E_1^*} (\Delta E_1)^2 + \frac{1}{2k_B} \left. \frac{\partial^2 S_2}{\partial E_2^2} \right|_{E_2^*} (\Delta E_1)^2 + \dots, \quad (4.69)$$

where  $E_2^* = E - E_1^*$ . We must now evaluate

$$\frac{\partial^2 S}{\partial E^2} = \frac{\partial}{\partial E} \left( \frac{1}{T} \right) = -\frac{1}{T^2} \left( \frac{\partial T}{\partial E} \right)_{V, N} = -\frac{1}{T^2 C_V}, \quad (4.70)$$



where  $C_V = (\partial E / \partial T)_{V,N}$  is the heat capacity. Thus,

$$P_1 = P_1^* e^{-(\Delta E_1)^2 / 2k_B T^2 \bar{C}_V}, \quad (4.71)$$

where

$$\bar{C}_V = \frac{C_{V,1} C_{V,2}}{C_{V,1} + C_{V,2}}. \quad (4.72)$$

The distribution is therefore a Gaussian, and the fluctuations in  $\Delta E_1$  can now be computed:

$$\langle (\Delta E_1)^2 \rangle = k_B T^2 \bar{C}_V \quad \implies \quad (\Delta E_1)_{\text{RMS}} = k_B T \sqrt{\bar{C}_V / k_B}. \quad (4.73)$$

The individual heat capacities  $C_{V,1}$  and  $C_{V,2}$  scale with the volumes  $V_1$  and  $V_2$ , respectively. If  $V_2 \gg V_1$ , then  $C_{V,2} \gg C_{V,1}$ , in which case  $\bar{C}_V \approx C_{V,1}$ . Therefore the RMS fluctuations in  $\Delta E_1$  are proportional to the *square root* of the system size, whereas  $E_1$  itself is extensive. Thus, the ratio  $(\Delta E_1)_{\text{RMS}} / E_1 \propto V^{-1/2}$  scales as the inverse square root of the volume. The distribution  $P_1(E_1)$  is thus *extremely sharp*.

#### 4.4.2 Thermal, mechanical and chemical equilibrium

Since

$$dS = \frac{1}{T} dE + \frac{p}{T} dV - \frac{\mu}{T} dN, \quad (4.74)$$

we can employ the same reasoning as in the previous section and conclude that entropy maximization guarantees the following:

- If two systems can exchange energy, then  $T_1 = T_2$ . This is *thermal equilibrium*.
- If two systems can exchange volume, then  $p_1/T_1 = p_2/T_2$ . This is *mechanical equilibrium*.
- If two systems can exchange particle number, then  $\mu_1/T_1 = \mu_2/T_2$ . This is *chemical equilibrium*.

### 4.5 Ordinary Canonical Ensemble (OCE)

#### 4.5.1 Canonical distribution and partition function

Consider a system  $S$  in contact with a world  $W$ , and let their union  $U = W \cup S$  be called the ‘universe’. The situation is depicted in fig. 4.2. The volume  $V_S$  and particle number  $N_S$  of the system are held fixed, but the energy is allowed to fluctuate by exchange with the world  $W$ . We are interested in the limit  $N_S \rightarrow \infty$ ,  $N_W \rightarrow \infty$ , with  $N_S \ll N_W$ , with similar relations holding for the respective volumes and energies. We now ask what is the probability that  $S$  is in a state  $|n\rangle$  with energy  $E_n$ . This is given by the ratio

$$\begin{aligned} P_n &= \lim_{\Delta E \rightarrow 0} \frac{D_W(E_U - E_n) \Delta E}{D_U(E_U) \Delta E} \\ &= \frac{\text{\# of states accessible to } W \text{ given that } E_S = E_n}{\text{total \# of states in } U}. \end{aligned} \quad (4.75)$$

Then

$$\begin{aligned}
\ln P_n &= \ln D_W(E_U - E_n) - \ln D_U(E_U) \\
&= \ln D_W(E_U) - \ln D_U(E_U) - E_n \left. \frac{\partial \ln D_W(E)}{\partial E} \right|_{E=E_U} + \dots \\
&\equiv -\alpha - \beta E_n .
\end{aligned} \tag{4.76}$$

The constant  $\beta$  is given by

$$\beta = \left. \frac{\partial \ln D_W(E)}{\partial E} \right|_{E=E_U} = \frac{1}{k_B T} . \tag{4.77}$$

Thus, we find  $P_n = e^{-\alpha} e^{-\beta E_n}$ . The constant  $\alpha$  is fixed by the requirement that  $\sum_n P_n = 1$ :

$$P_n = \frac{1}{Z} e^{-\beta E_n} \quad , \quad Z(T, V, N) = \sum_n e^{-\beta E_n} = \text{Tr} e^{-\beta \hat{H}} . \tag{4.78}$$

We've already met  $Z(\beta)$  in eqn. 4.23 – it is the Laplace transform of the density of states. It is also called the *partition function* of the system  $S$ . Quantum mechanically, we can write the ordinary canonical density matrix as

$$\hat{\rho} = \frac{e^{-\beta \hat{H}}}{\text{Tr} e^{-\beta \hat{H}}} . \tag{4.79}$$

Note that  $[\hat{\rho}, \hat{H}] = 0$ , hence the ordinary canonical distribution is a stationary solution to the evolution equation for the density matrix. Note that the OCE is specified by three parameters:  $T$ ,  $V$ , and  $N$ .

#### 4.5.2 The difference between $P(E_n)$ and $P_n$

Let the total energy of the Universe be fixed at  $E_U$ . The joint probability density  $P(E_S, E_W)$  for the system to have energy  $E_S$  and the world to have energy  $E_W$  is

$$P(E_S, E_W) = D_S(E_S) D_W(E_W) \delta(E_U - E_S - E_W) / D_U(E_U) , \tag{4.80}$$

where

$$D_U(E_U) = \int_{-\infty}^{\infty} dE_S D_S(E_S) D_W(E_U - E_S) , \tag{4.81}$$

which ensures that  $\int dE_S \int dE_W P(E_S, E_W) = 1$ . The *probability density*  $P(E_S)$  is defined such that  $P(E_S) dE_S$  is the (differential) probability for the system to have an energy in the range  $[E_S, E_S + dE_S]$ . The units of  $P(E_S)$  are  $E^{-1}$ . To obtain  $P(E_S)$ , we simply integrate the joint probability density  $P(E_S, E_W)$  over all possible values of  $E_W$ , obtaining

$$P(E_S) = \frac{D_S(E_S) D_W(E_U - E_S)}{D_U(E_U)} , \tag{4.82}$$

as we have in eqn. 4.75.

Now suppose we wish to know the probability  $P_n$  that the system is in a *particular* state  $|n\rangle$  with energy  $E_n$ . Clearly

$$P_n = \lim_{\Delta E \rightarrow 0} \frac{\text{probability that } E_s \in [E_n, E_n + \Delta E]}{\# \text{ of S states with } E_s \in [E_n, E_n + \Delta E]} = \frac{P(E_n) \Delta E}{D_s(E_n) \Delta E} = \frac{D_w(E_U - E_n)}{D_U(E_U)}. \quad (4.83)$$

### 4.5.3 Averages within the OCE

To compute averages within the OCE,

$$\langle \hat{A} \rangle = \text{Tr}(\hat{\rho} \hat{A}) = \frac{\sum_n \langle n | \hat{A} | n \rangle e^{-\beta E_n}}{\sum_n e^{-\beta E_n}}, \quad (4.84)$$

where we have conveniently taken the trace in a basis of energy eigenstates. In the classical limit, we have

$$\rho(\varphi) = \frac{1}{Z} e^{-\beta \hat{H}(\varphi)}, \quad Z = \text{Tr} e^{-\beta \hat{H}} = \int d\mu e^{-\beta \hat{H}(\varphi)}, \quad (4.85)$$

with  $d\mu = \frac{1}{N!} \prod_{j=1}^N (d^d q_j d^d p_j / h^d)$  for identical particles ('Maxwell-Boltzmann statistics'). Thus,

$$\langle A \rangle = \text{Tr}(\rho A) = \frac{\int d\mu A(\varphi) e^{-\beta \hat{H}(\varphi)}}{\int d\mu e^{-\beta \hat{H}(\varphi)}}. \quad (4.86)$$

### 4.5.4 Entropy and free energy

The *Boltzmann entropy* is defined by

$$S = -k_B \text{Tr}(\hat{\rho} \ln \hat{\rho}) = -k_B \sum_n P_n \ln P_n. \quad (4.87)$$

The Boltzmann entropy and the statistical entropy  $S = k_B \ln D(E)$  are identical in the thermodynamic limit.

We define the Helmholtz free energy  $F(T, V, N)$  as

$$F(T, V, N) = -k_B T \ln Z(T, V, N), \quad (4.88)$$

hence

$$P_n = e^{\beta F} e^{-\beta E_n}, \quad \ln P_n = \beta F - \beta E_n. \quad (4.89)$$

Therefore the entropy is

$$\begin{aligned} S &= -k_B \sum_n P_n (\beta F - \beta E_n) \\ &= -\frac{F}{T} + \frac{\langle \hat{H} \rangle}{T}, \end{aligned} \quad (4.90)$$

which is to say

$$F = E - TS, \quad (4.91)$$

where

$$E = \sum_n P_n E_n = \frac{\text{Tr } \hat{H} e^{-\beta \hat{H}}}{\text{Tr } e^{-\beta \hat{H}}} \quad (4.92)$$

is the average energy. We also see that

$$Z = \text{Tr } e^{-\beta \hat{H}} = \sum_n e^{-\beta E_n} \implies E = \frac{\sum_n E_n e^{-\beta E_n}}{\sum_n e^{-\beta E_n}} = -\frac{\partial}{\partial \beta} \ln Z = \frac{\partial}{\partial \beta} (\beta F). \quad (4.93)$$

Thus,  $F(T, V, N)$  is a Legendre transform of  $E(S, V, N)$ , with

$$dF = -S dT - p dV + \mu dN, \quad (4.94)$$

which means

$$S = -\left(\frac{\partial F}{\partial T}\right)_{V,N}, \quad p = -\left(\frac{\partial F}{\partial V}\right)_{T,N}, \quad \mu = +\left(\frac{\partial F}{\partial N}\right)_{T,V}. \quad (4.95)$$

#### 4.5.5 Fluctuations in the OCE

In the OCE, the energy is not fixed. It therefore fluctuates about its average value  $E = \langle \hat{H} \rangle$ . Note that

$$\begin{aligned} -\frac{\partial E}{\partial \beta} &= k_B T^2 \frac{\partial E}{\partial T} = \frac{\partial^2 \ln Z}{\partial \beta^2} \\ &= \frac{\text{Tr } \hat{H}^2 e^{-\beta \hat{H}}}{\text{Tr } e^{-\beta \hat{H}}} - \left( \frac{\text{Tr } \hat{H} e^{-\beta \hat{H}}}{\text{Tr } e^{-\beta \hat{H}}} \right)^2 \\ &= \langle \hat{H}^2 \rangle - \langle \hat{H} \rangle^2. \end{aligned} \quad (4.96)$$

Thus, the heat capacity is related to the fluctuations in the energy, just as we saw at the end of §4.4:

$$C_V = \left(\frac{\partial E}{\partial T}\right)_{V,N} = \frac{1}{k_B T^2} \left( \langle \hat{H}^2 \rangle - \langle \hat{H} \rangle^2 \right) \quad (4.97)$$

For the nonrelativistic ideal gas, we found  $C_V = \frac{d}{2} N k_B$ , hence the ratio of RMS fluctuations in the energy to the energy itself is

$$\frac{\sqrt{\langle (\Delta \hat{H})^2 \rangle}}{\langle \hat{H} \rangle} = \frac{\sqrt{k_B T^2 C_V}}{\frac{d}{2} N k_B T} = \sqrt{\frac{2}{Nd}}, \quad (4.98)$$

and the ratio of the RMS fluctuations to the mean value vanishes in the thermodynamic limit.

The full distribution function for the energy is

$$P(\mathcal{E}) = \langle \delta(\mathcal{E} - \hat{H}) \rangle = \frac{\text{Tr } \delta(\mathcal{E} - \hat{H}) e^{-\beta \hat{H}}}{\text{Tr } e^{-\beta \hat{H}}} = \frac{1}{Z} D(\mathcal{E}) e^{-\beta \mathcal{E}}. \quad (4.99)$$

Thus,

$$P(\mathcal{E}) = \frac{e^{-\beta[\mathcal{E}-TS(\mathcal{E})]}}{\int d\tilde{\mathcal{E}} e^{-\beta[\tilde{\mathcal{E}}-TS(\tilde{\mathcal{E}})]}}, \quad (4.100)$$

where  $S(\mathcal{E}) = k_B \ln D(\mathcal{E})$  is the statistical entropy. Let's write  $\mathcal{E} = E + \delta\mathcal{E}$ , where  $E$  extremizes the combination  $\mathcal{E} - TS(\mathcal{E})$ , *i.e.* the solution to  $T S'(E) = 1$ , where the energy derivative of  $S$  is performed at fixed volume  $V$  and particle number  $N$ . We now expand  $S(E + \delta\mathcal{E})$  to second order in  $\delta\mathcal{E}$ , obtaining

$$S(E + \delta\mathcal{E}) = S(E) + \frac{\delta\mathcal{E}}{T} - \frac{(\delta\mathcal{E})^2}{2T^2 C_V} + \dots \quad (4.101)$$

Recall that  $S''(E) = \frac{\partial}{\partial E} \left( \frac{1}{T} \right) = -\frac{1}{T^2 C_V}$ . Thus,

$$\mathcal{E} - TS(\mathcal{E}) = E - TS(E) + \frac{(\delta\mathcal{E})^2}{2T C_V} + \mathcal{O}((\delta\mathcal{E})^2). \quad (4.102)$$

Applying this to both numerator and denominator of eqn. 4.100, we obtain<sup>4</sup>

$$P(\mathcal{E}) = \mathcal{N} \exp \left[ -\frac{(\delta\mathcal{E})^2}{2k_B T^2 C_V} \right], \quad (4.103)$$

where  $\mathcal{N} = (2\pi k_B T^2 C_V)^{-1/2}$  is a normalization constant which guarantees  $\int d\mathcal{E} P(\mathcal{E}) = 1$ . Once again, we see that the distribution is a Gaussian centered at  $\langle \mathcal{E} \rangle = E$ , and of width  $(\Delta\mathcal{E})_{\text{RMS}} = \sqrt{k_B T^2 C_V}$ . This is a consequence of the Central Limit Theorem.

#### 4.5.6 Thermodynamics revisited

The average energy within the OCE is

$$E = \sum_n E_n P_n, \quad (4.104)$$

and therefore

$$\begin{aligned} dE &= \sum_n E_n dP_n + \sum_n P_n dE_n \\ &= dQ - dW, \end{aligned} \quad (4.105)$$

where

$$dW = -\sum_n P_n dE_n \quad (4.106)$$

$$dQ = \sum_n E_n dP_n. \quad (4.107)$$

---

<sup>4</sup>In applying eqn. 4.102 to the denominator of eqn. 4.100, we shift  $\tilde{\mathcal{E}}$  by  $E$  and integrate over the difference  $\delta\tilde{\mathcal{E}} \equiv \tilde{\mathcal{E}} - E$ , retaining terms up to quadratic order in  $\delta\tilde{\mathcal{E}}$  in the argument of the exponent.

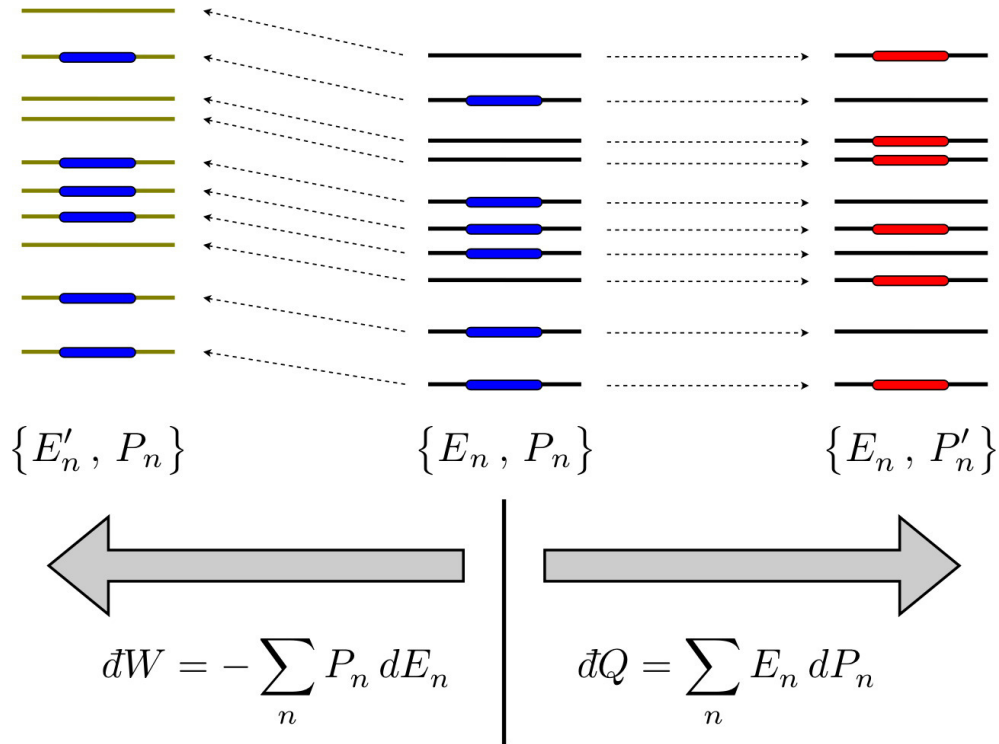


Figure 4.5: Microscopic, statistical interpretation of the First Law of Thermodynamics.

Finally, from  $P_n = Z^{-1} e^{-E_n/k_B T}$ , we can write

$$E_n = -k_B T \ln Z - k_B T \ln P_n, \quad (4.108)$$

with which we obtain

$$\begin{aligned} dQ &= \sum_n E_n dP_n \\ &= -k_B T \ln Z \sum_n dP_n - k_B T \sum_n \ln P_n dP_n \\ &= T d\left(-k_B \sum_n P_n \ln P_n\right) = T dS. \end{aligned} \quad (4.109)$$

Note also that

$$\begin{aligned} dW &= -\sum_n P_n dE_n \\ &= -\sum_n P_n \left( \sum_i \frac{\partial E_n}{\partial X_i} dX_i \right) \\ &= -\sum_{n,i} P_n \langle n | \frac{\partial \hat{H}}{\partial X_i} | n \rangle dX_i \equiv \sum_i F_i dX_i, \end{aligned} \quad (4.110)$$

so the generalized force  $F_i$  conjugate to the generalized displacement  $dX_i$  is

$$F_i = - \sum_n P_n \frac{\partial E_n}{\partial X_i} = - \left\langle \frac{\partial \hat{H}}{\partial X_i} \right\rangle. \quad (4.111)$$

This is the force acting *on* the system<sup>5</sup>. In the chapter on thermodynamics, we defined the generalized force conjugate to  $X_i$  as  $y_i \equiv -F_i$ .

Thus we see from eqn. 4.105 that there are two ways that the average energy can change; these are depicted in the sketch of fig. 4.5. Starting from a set of energy levels  $\{E_n\}$  and probabilities  $\{P_n\}$ , we can shift the energies to  $\{E'_n\}$ . The resulting change in energy  $(\Delta E)_I = -W$  is identified with the work done *on* the system. We could also modify the probabilities to  $\{P'_n\}$  without changing the energies. The energy change in this case is the heat absorbed *by* the system:  $(\Delta E)_{II} = Q$ . This provides us with a statistical and microscopic interpretation of the First Law of Thermodynamics.

### 4.5.7 Generalized susceptibilities

Suppose our Hamiltonian is of the form

$$\hat{H} = \hat{H}(\lambda) = \hat{H}_0 - \lambda \hat{Q}, \quad (4.112)$$

where  $\lambda$  is an intensive parameter, such as magnetic field. Then

$$Z(\lambda) = \text{Tr} e^{-\beta(\hat{H}_0 - \lambda \hat{Q})} \quad (4.113)$$

and

$$\frac{1}{Z} \frac{\partial Z}{\partial \lambda} = \beta \cdot \frac{1}{Z} \text{Tr} \left( \hat{Q} e^{-\beta \hat{H}(\lambda)} \right) = \beta \langle \hat{Q} \rangle. \quad (4.114)$$

But then from  $Z = e^{-\beta F}$  we have

$$Q(\lambda, T) = \langle \hat{Q} \rangle = - \left( \frac{\partial F}{\partial \lambda} \right)_T. \quad (4.115)$$

Typically we will take  $Q$  to be an extensive quantity. We can now define the *susceptibility*  $\chi$  as

$$\chi = \frac{1}{V} \frac{\partial Q}{\partial \lambda} = - \frac{1}{V} \frac{\partial^2 F}{\partial \lambda^2}. \quad (4.116)$$

The volume factor in the denominator ensures that  $\chi$  is intensive.

It is important to realize that we have assumed here that  $[\hat{H}_0, \hat{Q}] = 0$ , *i.e.* the 'bare' Hamiltonian  $\hat{H}_0$  and the operator  $\hat{Q}$  commute. If they do not commute, then the response functions must be computed within a proper quantum mechanical formalism, which we shall not discuss here.

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<sup>5</sup>In deriving eqn. 4.111, we have used the so-called Feynman-Hellman theorem of quantum mechanics:  $d\langle n | \hat{H} | n \rangle = \langle n | d\hat{H} | n \rangle$ , if  $|n\rangle$  is an energy eigenstate.

Note also that we can imagine an entire family of observables  $\{\hat{Q}_k\}$  satisfying  $[\hat{Q}_k, \hat{Q}_{k'}] = 0$  and  $[\hat{H}_0, \hat{Q}_k] = 0$ , for all  $k$  and  $k'$ . Then for the Hamiltonian

$$\hat{H}(\vec{\lambda}) = \hat{H}_0 - \sum_k \lambda_k \hat{Q}_k, \quad (4.117)$$

we have that

$$Q_k(\vec{\lambda}, T) = \langle \hat{Q}_k \rangle = - \left( \frac{\partial F}{\partial \lambda_k} \right)_{T, N_a, \lambda_{k' \neq k}} \quad (4.118)$$

and we may define an entire matrix of susceptibilities,

$$\chi_{kl} = \frac{1}{V} \frac{\partial Q_k}{\partial \lambda_l} = - \frac{1}{V} \frac{\partial^2 F}{\partial \lambda_k \partial \lambda_l}. \quad (4.119)$$

## 4.6 Grand Canonical Ensemble (GCE)

### 4.6.1 Grand canonical distribution and partition function

Consider once again the situation depicted in fig. 4.2, where a system  $S$  is in contact with a world  $W$ , their union  $U = W \cup S$  being called the 'universe'. We assume that the system's volume  $V_s$  is fixed, but otherwise it is allowed to exchange energy and particle number with  $W$ . Hence, the system's energy  $E_s$  and particle number  $N_s$  will fluctuate. We ask what is the probability that  $S$  is in a state  $|n\rangle$  with energy  $E_n$  and particle number  $N_n$ . This is given by the ratio

$$\begin{aligned} P_n &= \lim_{\Delta E \rightarrow 0} \frac{D_w(E_U - E_n, N_U - N_n) \Delta E}{D_U(E_U, N_U) \Delta E} \\ &= \frac{\# \text{ of states accessible to } W \text{ given that } E_s = E_n \text{ and } N_s = N_n}{\text{total \# of states in } U}. \end{aligned} \quad (4.120)$$

Then

$$\begin{aligned} \ln P_n &= \ln D_w(E_U - E_n, N_U - N_n) - \ln D_U(E_U, N_U) \\ &= \ln D_w(E_U, N_U) - \ln D_U(E_U, N_U) \\ &\quad - E_n \left. \frac{\partial \ln D_w(E, N)}{\partial E} \right|_{\substack{E=E_U \\ N=N_U}} - N_n \left. \frac{\partial \ln D_w(E, N)}{\partial N} \right|_{\substack{E=E_U \\ N=N_U}} + \dots \\ &\equiv -\alpha - \beta E_n + \beta \mu N_n. \end{aligned} \quad (4.121)$$



The constants  $\beta$  and  $\mu$  are given by

$$\beta = \left. \frac{\partial \ln D_w(E, N)}{\partial E} \right|_{\substack{E=E_U \\ N=N_U}} = \frac{1}{k_B T} \quad (4.122)$$

$$\mu = -k_B T \left. \frac{\partial \ln D_w(E, N)}{\partial N} \right|_{\substack{E=E_U \\ N=N_U}}. \quad (4.123)$$

The quantity  $\mu$  has dimensions of energy and is called the *chemical potential*. *Nota bene*: Some texts define the ‘grand canonical Hamiltonian’  $\hat{K}$  as

$$\hat{K} \equiv \hat{H} - \mu \hat{N}. \quad (4.124)$$

Thus,  $P_n = e^{-\alpha} e^{-\beta(E_n - \mu N_n)}$ . Once again, the constant  $\alpha$  is fixed by the requirement that  $\sum_n P_n = 1$ :

$$P_n = \frac{1}{\Xi} e^{-\beta(E_n - \mu N_n)}, \quad \Xi(\beta, V, \mu) = \sum_n e^{-\beta(E_n - \mu N_n)} = \text{Tr} e^{-\beta(\hat{H} - \mu \hat{N})} = \text{Tr} e^{-\beta \hat{K}}. \quad (4.125)$$

Thus, the quantum mechanical *grand canonical density matrix* is given by

$$\hat{\rho} = \frac{e^{-\beta \hat{K}}}{\text{Tr} e^{-\beta \hat{K}}}. \quad (4.126)$$

Note that  $[\hat{\rho}, \hat{K}] = 0$ .

The quantity  $\Xi(T, V, \mu)$  is called the *grand partition function*. It stands in relation to a corresponding free energy in the usual way:

$$\Xi(T, V, \mu) \equiv e^{-\beta \Omega(T, V, \mu)} \iff \Omega = -k_B T \ln \Xi, \quad (4.127)$$

where  $\Omega(T, V, \mu)$  is the *grand potential*, also known as the *Landau free energy*. The dimensionless quantity  $z \equiv e^{\beta \mu}$  is called the *fugacity*.

If  $[\hat{H}, \hat{N}] = 0$ , the grand potential may be expressed as a sum over contributions from each  $N$  sector, *viz.*

$$\Xi(T, V, \mu) = \sum_N e^{\beta \mu N} Z(T, V, N). \quad (4.128)$$

When there is more than one species, we have several chemical potentials  $\{\mu_a\}$ , and accordingly we define

$$\hat{K} = \hat{H} - \sum_a \mu_a \hat{N}_a, \quad (4.129)$$

with  $\Xi = \text{Tr} e^{-\beta \hat{K}}$  as before.

### 4.6.2 Entropy and Gibbs-Duhem relation

In the GCE, the Boltzmann entropy is

$$\begin{aligned}
 S &= -k_B \sum_n P_n \ln P_n \\
 &= -k_B \sum_n P_n \left( \beta \Omega - \beta E_n + \beta \mu N_n \right) \\
 &= -\frac{\Omega}{T} + \frac{\langle \hat{H} \rangle}{T} - \frac{\mu \langle \hat{N} \rangle}{T},
 \end{aligned} \tag{4.130}$$

which says

$$\Omega = E - TS - \mu N, \tag{4.131}$$

where

$$E = \sum_n E_n P_n = \text{Tr} (\hat{\rho} \hat{H}) \tag{4.132}$$

$$N = \sum_n N_n P_n = \text{Tr} (\hat{\rho} \hat{N}). \tag{4.133}$$

Therefore,  $\Omega(T, V, \mu)$  is a double Legendre transform of  $E(S, V, N)$ , with

$$d\Omega = -S dT - p dV - N d\mu, \tag{4.134}$$

which entails

$$S = - \left( \frac{\partial \Omega}{\partial T} \right)_{V, \mu}, \quad p = - \left( \frac{\partial \Omega}{\partial V} \right)_{T, \mu}, \quad N = - \left( \frac{\partial \Omega}{\partial \mu} \right)_{T, V}. \tag{4.135}$$

Since  $\Omega(T, V, \mu)$  is an extensive quantity, we must be able to write  $\Omega = V\omega(T, \mu)$ . We identify the function  $\omega(T, \mu)$  as the negative of the pressure:

$$\begin{aligned}
 \frac{\partial \Omega}{\partial V} &= -\frac{k_B T}{\Xi} \left( \frac{\partial \Xi}{\partial V} \right)_{T, \mu} = \frac{1}{\Xi} \sum_n \frac{\partial E_n}{\partial V} e^{-\beta(E_n - \mu N_n)} \\
 &= \left( \frac{\partial E}{\partial V} \right)_{T, \mu} = -p(T, \mu).
 \end{aligned} \tag{4.136}$$

Therefore,

$$\Omega = -pV, \quad p = p(T, \mu) \quad (\text{equation of state}). \tag{4.137}$$

This is consistent with the result from thermodynamics that  $G = E - TS + pV = \mu N$ . Taking the differential, we obtain the Gibbs-Duhem relation,

$$d\Omega = -S dT - p dV - N d\mu = -p dV - V dp \Rightarrow S dT - V dp + N d\mu = 0. \tag{4.138}$$

### 4.6.3 Generalized susceptibilities in the GCE

We can appropriate the results from §4.5.7 and apply them, *mutatis mutandis*, to the GCE. Suppose we have a family of observables  $\{\hat{Q}_k\}$  satisfying  $[\hat{Q}_k, \hat{Q}_{k'}] = 0$  and  $[\hat{H}_0, \hat{Q}_k] = 0$  and  $[\hat{N}_a, \hat{Q}_k] = 0$  for all  $k, k'$ , and  $a$ . Then for the grand canonical Hamiltonian

$$\hat{K}(\vec{\lambda}) = \hat{H}_0 - \sum_a \mu_a \hat{N}_a - \sum_k \lambda_k \hat{Q}_k, \quad (4.139)$$

we have that

$$Q_k(\vec{\lambda}, T) = \langle \hat{Q}_k \rangle = - \left( \frac{\partial \Omega}{\partial \lambda_k} \right)_{T, \mu_a, \lambda_{k' \neq k}} \quad (4.140)$$

and we may define the matrix of generalized susceptibilities,

$$\chi_{kl} = \frac{1}{V} \frac{\partial Q_k}{\partial \lambda_l} = - \frac{1}{V} \frac{\partial^2 \Omega}{\partial \lambda_k \partial \lambda_l}. \quad (4.141)$$

### 4.6.4 Fluctuations in the GCE

Both energy and particle number fluctuate in the GCE. Let us compute the fluctuations in particle number. We have

$$N = \langle \hat{N} \rangle = \frac{\text{Tr} \hat{N} e^{-\beta(\hat{H} - \mu \hat{N})}}{\text{Tr} e^{-\beta(\hat{H} - \mu \hat{N})}} = \frac{1}{\beta} \frac{\partial}{\partial \mu} \ln \Xi. \quad (4.142)$$

Therefore,

$$\begin{aligned} \frac{1}{\beta} \frac{\partial N}{\partial \mu} &= \frac{\text{Tr} \hat{N}^2 e^{-\beta(\hat{H} - \mu \hat{N})}}{\text{Tr} e^{-\beta(\hat{H} - \mu \hat{N})}} - \left( \frac{\text{Tr} \hat{N} e^{-\beta(\hat{H} - \mu \hat{N})}}{\text{Tr} e^{-\beta(\hat{H} - \mu \hat{N})}} \right)^2 \\ &= \langle \hat{N}^2 \rangle - \langle \hat{N} \rangle^2. \end{aligned} \quad (4.143)$$

Note now that

$$\frac{\langle \hat{N}^2 \rangle - \langle \hat{N} \rangle^2}{\langle \hat{N} \rangle^2} = \frac{k_B T}{N^2} \left( \frac{\partial N}{\partial \mu} \right)_{T, V} = \frac{k_B T}{V} \kappa_T, \quad (4.144)$$

where  $\kappa_T$  is the isothermal compressibility. Note:

$$\begin{aligned} \left( \frac{\partial N}{\partial \mu} \right)_{T, V} &= \frac{\partial(N, T, V)}{\partial(\mu, T, V)} = - \frac{\partial(N, T, V)}{\partial(V, T, \mu)} \\ &= - \frac{\partial(N, T, V)}{\partial(N, T, p)} \cdot \frac{\partial(N, T, p)}{\partial(V, T, p)} \cdot \overbrace{\frac{\partial(V, T, p)}{\partial(N, T, \mu)}}^1 \cdot \frac{\partial(N, T, \mu)}{\partial(V, T, \mu)} \\ &= - \frac{N^2}{V^2} \left( \frac{\partial V}{\partial p} \right)_{T, N} = \frac{N^2}{V} \kappa_T. \end{aligned} \quad (4.145)$$

Thus,

$$\frac{(\Delta N)_{\text{RMS}}}{N} = \sqrt{\frac{k_{\text{B}} T \kappa_T}{V}}, \quad (4.146)$$

which again scales as  $V^{-1/2}$ .

#### 4.6.5 Gibbs ensemble

Let the system's particle number  $N$  be fixed, but let it exchange energy and volume with the world  $W$ . *Mutatis mutandis*, we have

$$P_n = \lim_{\Delta E \rightarrow 0} \lim_{\Delta V \rightarrow 0} \frac{D_{\text{w}}(E_{\text{U}} - E_n, V_{\text{U}} - V_n) \Delta E \Delta V}{D_{\text{U}}(E_{\text{U}}, V_{\text{U}}) \Delta E \Delta V}. \quad (4.147)$$

Then

$$\begin{aligned} \ln P_n &= \ln D_{\text{w}}(E_{\text{U}} - E_n, V_{\text{U}} - V_n) - \ln D_{\text{U}}(E_{\text{U}}, V_{\text{U}}) \\ &= \ln D_{\text{w}}(E_{\text{U}}, V_{\text{U}}) - \ln D_{\text{U}}(E_{\text{U}}, V_{\text{U}}) \\ &\quad - E_n \left. \frac{\partial \ln D_{\text{w}}(E, V)}{\partial E} \right|_{\substack{E=E_{\text{U}} \\ V=V_{\text{U}}}} - V_n \left. \frac{\partial \ln D_{\text{w}}(E, V)}{\partial V} \right|_{\substack{E=E_{\text{U}} \\ V=V_{\text{U}}}} + \dots \\ &\equiv -\alpha - \beta E_n - \beta p V_n. \end{aligned} \quad (4.148)$$

The constants  $\beta$  and  $p$  are given by

$$\beta = \left. \frac{\partial \ln D_{\text{w}}(E, V)}{\partial E} \right|_{\substack{E=E_{\text{U}} \\ V=V_{\text{U}}}} = \frac{1}{k_{\text{B}} T} \quad (4.149)$$

$$p = k_{\text{B}} T \left. \frac{\partial \ln D_{\text{w}}(E, V)}{\partial V} \right|_{\substack{E=E_{\text{U}} \\ V=V_{\text{U}}}}. \quad (4.150)$$

The corresponding partition function is

$$Y(T, p, N) = \text{Tr} e^{-\beta(\hat{H}+pV)} = \frac{1}{V_0} \int_0^{\infty} dV e^{-\beta p V} Z(T, V, N) \equiv e^{-\beta G(T, p, N)}, \quad (4.151)$$

where  $V_0$  is a constant which has dimensions of volume. The factor  $V_0^{-1}$  in front of the integral renders  $Y$  dimensionless. Note that  $G(V'_0) = G(V_0) + k_{\text{B}} T \ln(V'_0/V_0)$ , so the difference is not extensive and can be neglected in the thermodynamic limit. In other words, it doesn't matter what constant we choose for  $V_0$  since it contributes subextensively to  $G$ . Moreover, in computing averages, the constant  $V_0$  divides out in the ratio of numerator and denominator. Like the Helmholtz free energy, the Gibbs free energy  $G(T, p, N)$  is also a double Legendre transform of the energy  $E(S, V, N)$ , *viz.*

$$\begin{aligned} G &= E - TS + pV \\ dG &= -S dT + V dp + \mu dN, \end{aligned} \quad (4.152)$$

which entails

$$S = - \left( \frac{\partial G}{\partial T} \right)_{p,N} , \quad V = + \left( \frac{\partial G}{\partial p} \right)_{T,N} , \quad \mu = + \left( \frac{\partial G}{\partial N} \right)_{T,p} . \quad (4.153)$$

## 4.7 Statistical Ensembles from Maximum Entropy

The basic principle: maximize the entropy,

$$S = -k_B \sum_n P_n \ln P_n . \quad (4.154)$$

### 4.7.1 $\mu$ CE

We maximize  $S$  subject to the single constraint

$$C = \sum_n P_n - 1 = 0 . \quad (4.155)$$

We implement the constraint  $C = 0$  with a Lagrange multiplier,  $\bar{\lambda} \equiv k_B \lambda$ , writing

$$S^* = S - k_B \lambda C , \quad (4.156)$$

and freely extremizing over the distribution  $\{P_n\}$  and the Lagrange multiplier  $\lambda$ . Thus,

$$\begin{aligned} \delta S^* &= \delta S - k_B \lambda \delta C - k_B C \delta \lambda \\ &= -k_B \sum_n \left[ \ln P_n + 1 + \lambda \right] \delta P_n - k_B C \delta \lambda \equiv 0 . \end{aligned} \quad (4.157)$$

We conclude that  $C = 0$  and that

$$\ln P_n = -(1 + \lambda) , \quad (4.158)$$

and we fix  $\lambda$  by the normalization condition  $\sum_n P_n = 1$ . This gives

$$P_n = \frac{1}{\Omega} , \quad \Omega = \sum_n \Theta(E + \Delta E - E_n) \Theta(E_n - E) . \quad (4.159)$$

Note that  $\Omega$  is the number of states with energies between  $E$  and  $E + \Delta E$ .

### 4.7.2 OCE

We maximize  $S$  subject to the two constraints

$$C_1 = \sum_n P_n - 1 = 0 , \quad C_2 = \sum_n E_n P_n - E = 0 . \quad (4.160)$$

We now have two Lagrange multipliers. We write

$$S^* = S - k_B \sum_{j=1}^2 \lambda_j C_j, \quad (4.161)$$

and we freely extremize over  $\{P_n\}$  and  $\{C_j\}$ . We therefore have

$$\begin{aligned} \delta S^* &= \delta S - k_B \sum_n (\lambda_1 + \lambda_2 E_n) \delta P_n - k_B \sum_{j=1}^2 C_j \delta \lambda_j \\ &= -k_B \sum_n \left[ \ln P_n + 1 + \lambda_1 + \lambda_2 E_n \right] \delta P_n - k_B \sum_{j=1}^2 C_j \delta \lambda_j \equiv 0. \end{aligned} \quad (4.162)$$

Thus,  $C_1 = C_2 = 0$  and

$$\ln P_n = -(1 + \lambda_1 + \lambda_2 E_n). \quad (4.163)$$

We define  $\lambda_2 \equiv \beta$  and we fix  $\lambda_1$  by normalization. This yields

$$P_n = \frac{1}{Z} e^{-\beta E_n}, \quad Z = \sum_n e^{-\beta E_n}. \quad (4.164)$$

### 4.7.3 GCE

We maximize  $S$  subject to the three constraints

$$C_1 = \sum_n P_n - 1 = 0, \quad C_2 = \sum_n E_n P_n - E = 0, \quad C_3 = \sum_n N_n P_n - N = 0. \quad (4.165)$$

We now have three Lagrange multipliers. We write

$$S^* = S - k_B \sum_{j=1}^3 \lambda_j C_j, \quad (4.166)$$

and hence

$$\begin{aligned} \delta S^* &= \delta S - k_B \sum_n (\lambda_1 + \lambda_2 E_n + \lambda_3 N_n) \delta P_n - k_B \sum_{j=1}^3 C_j \delta \lambda_j \\ &= -k_B \sum_n \left[ \ln P_n + 1 + \lambda_1 + \lambda_2 E_n + \lambda_3 N_n \right] \delta P_n - k_B \sum_{j=1}^3 C_j \delta \lambda_j \equiv 0. \end{aligned} \quad (4.167)$$

Thus,  $C_1 = C_2 = C_3 = 0$  and

$$\ln P_n = -(1 + \lambda_1 + \lambda_2 E_n + \lambda_3 N_n). \quad (4.168)$$

We define  $\lambda_2 \equiv \beta$  and  $\lambda_3 \equiv -\beta\mu$ , and we fix  $\lambda_1$  by normalization. This yields

$$P_n = \frac{1}{\Xi} e^{-\beta(E_n - \mu N_n)}, \quad \Xi = \sum_n e^{-\beta(E_n - \mu N_n)}. \quad (4.169)$$

## 4.8 Ideal Gas Statistical Mechanics

The ordinary canonical partition function for the ideal gas was computed in eqn. 4.25. We found

$$\begin{aligned}
 Z(T, V, N) &= \frac{1}{N!} \prod_{i=1}^N \int \frac{d^d x_i d^d p_i}{(2\pi\hbar)^d} e^{-\beta p_i^2/2m} \\
 &= \frac{V^N}{N!} \left( \int_{-\infty}^{\infty} \frac{dp}{2\pi\hbar} e^{-\beta p^2/2m} \right)^{Nd} \\
 &= \frac{1}{N!} \left( \frac{V}{\lambda_T^d} \right)^N,
 \end{aligned} \tag{4.170}$$

where  $\lambda_T$  is the *thermal wavelength*:

$$\lambda_T = \sqrt{2\pi\hbar^2/mk_B T}. \tag{4.171}$$

The physical interpretation of  $\lambda_T$  is that it is the de Broglie wavelength for a particle of mass  $m$  which has a kinetic energy of  $k_B T$ .

In the GCE, we have

$$\begin{aligned}
 \Xi(T, V, \mu) &= \sum_{N=0}^{\infty} e^{\beta\mu N} Z(T, V, N) \\
 &= \sum_{N=0}^{\infty} \frac{1}{N!} \left( \frac{V e^{\mu/k_B T}}{\lambda_T^d} \right)^N = \exp \left( \frac{V e^{\mu/k_B T}}{\lambda_T^d} \right).
 \end{aligned} \tag{4.172}$$

From  $\Xi = e^{-\Omega/k_B T}$ , we have the grand potential is

$$\Omega(T, V, \mu) = -V k_B T e^{\mu/k_B T} / \lambda_T^d. \tag{4.173}$$

Since  $\Omega = -pV$  (see §4.6.2), we have

$$p(T, \mu) = k_B T \lambda_T^{-d} e^{\mu/k_B T}. \tag{4.174}$$

The number density can also be calculated:

$$n = \frac{N}{V} = -\frac{1}{V} \left( \frac{\partial \Omega}{\partial \mu} \right)_{T, V} = \lambda_T^{-d} e^{\mu/k_B T}. \tag{4.175}$$

Combined, the last two equations recapitulate the ideal gas law,  $pV = Nk_B T$ .

### 4.8.1 Maxwell velocity distribution

The distribution function for momenta is given by

$$g(\mathbf{p}) = \left\langle \frac{1}{N} \sum_{i=1}^N \delta(\mathbf{p}_i - \mathbf{p}) \right\rangle. \tag{4.176}$$

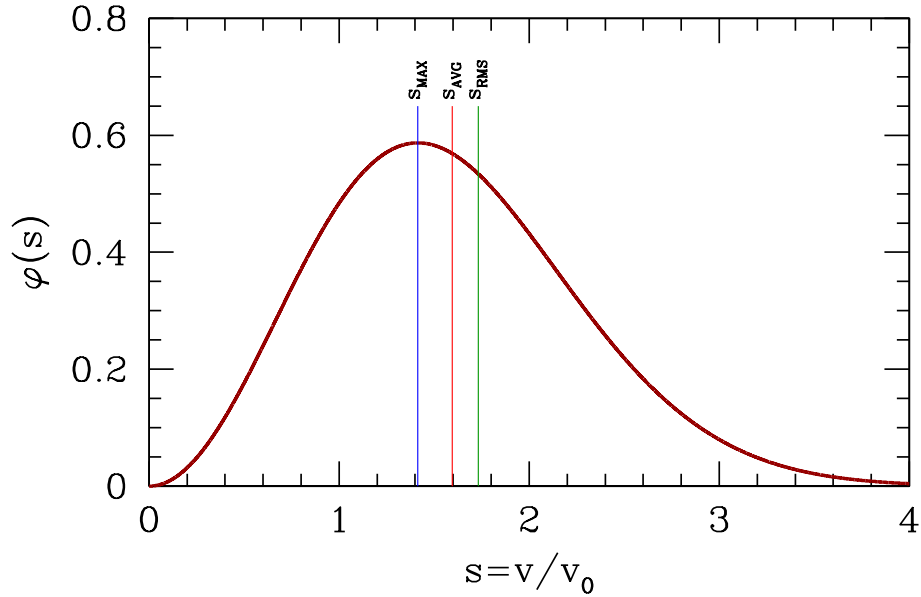


Figure 4.6: Maxwell distribution of speeds  $\varphi(v/v_0)$ . The most probable speed is  $v_{\text{MAX}} = \sqrt{2} v_0$ . The average speed is  $v_{\text{AVG}} = \sqrt{\frac{8}{\pi}} v_0$ . The RMS speed is  $v_{\text{RMS}} = \sqrt{3} v_0$ .

Note that  $g(\mathbf{p}) = \langle \delta(\mathbf{p}_i - \mathbf{p}) \rangle$  is the same for every particle, independent of its label  $i$ . We compute the average  $\langle A \rangle = \text{Tr} (A e^{-\beta \hat{H}}) / \text{Tr} e^{-\beta \hat{H}}$ . Setting  $i = 1$ , all the integrals other than that over  $\mathbf{p}_1$  divide out between numerator and denominator. We then have

$$\begin{aligned} g(\mathbf{p}) &= \frac{\int d^3 p_1 \delta(\mathbf{p}_1 - \mathbf{p}) e^{-\beta \mathbf{p}_1^2 / 2m}}{\int d^3 p_1 e^{-\beta \mathbf{p}_1^2 / 2m}} \\ &= (2\pi m k_B T)^{-3/2} e^{-\beta \mathbf{p}^2 / 2m}. \end{aligned} \quad (4.177)$$

Textbooks commonly refer to the *velocity distribution*  $f(\mathbf{v})$ , which is related to  $g(\mathbf{p})$  by

$$f(\mathbf{v}) d^3 v = g(\mathbf{p}) d^3 p. \quad (4.178)$$

Hence,

$$f(\mathbf{v}) = \left( \frac{m}{2\pi k_B T} \right)^{3/2} e^{-m\mathbf{v}^2 / 2k_B T}. \quad (4.179)$$

This is known as the *Maxwell velocity distribution*. Note that the distributions are normalized, *viz.*

$$\int d^3 p g(\mathbf{p}) = \int d^3 v f(\mathbf{v}) = 1. \quad (4.180)$$

If we are only interested in averaging functions of  $v = |\mathbf{v}|$  which are isotropic, then we can define the *Maxwell speed distribution*,  $\tilde{f}(v)$ , as

$$\tilde{f}(v) = 4\pi v^2 f(\mathbf{v}) = 4\pi \left( \frac{m}{2\pi k_B T} \right)^{3/2} v^2 e^{-mv^2 / 2k_B T}. \quad (4.181)$$



Note that  $\tilde{f}(v)$  is normalized according to

$$\int_0^{\infty} dv \tilde{f}(v) = 1. \quad (4.182)$$

It is convenient to represent  $v$  in units of  $v_0 = \sqrt{k_B T/m}$ , in which case

$$\tilde{f}(v) = \frac{1}{v_0} \varphi(v/v_0) \quad , \quad \varphi(s) = \sqrt{\frac{2}{\pi}} s^2 e^{-s^2/2}. \quad (4.183)$$

The distribution  $\varphi(s)$  is shown in fig. 4.6. Computing averages, we have

$$C_k \equiv \langle s^k \rangle = \int_0^{\infty} ds s^k \varphi(s) = 2^{k/2} \cdot \frac{2}{\sqrt{\pi}} \Gamma\left(\frac{3}{2} + \frac{k}{2}\right). \quad (4.184)$$

Thus,  $C_0 = 1$ ,  $C_1 = \sqrt{\frac{8}{\pi}}$ ,  $C_2 = 3$ , etc. The speed averages are

$$\langle v^k \rangle = C_k \left( \frac{k_B T}{m} \right)^{k/2}. \quad (4.185)$$

Note that the average *velocity* is  $\langle v \rangle = 0$ , but the average *speed* is  $\langle v \rangle = \sqrt{8k_B T/\pi m}$ . The speed distribution is plotted in fig. 4.6.

## 4.8.2 Equipartition

The Hamiltonian for ballistic (*i.e.* massive nonrelativistic) particles is quadratic in the individual components of each momentum  $p_i$ . There are other cases in which a classical degree of freedom appears quadratically in  $\hat{H}$  as well. For example, an individual normal mode  $\xi$  of a system of coupled oscillators has the Lagrangian

$$L = \frac{1}{2} \dot{\xi}^2 - \frac{1}{2} \omega_0^2 \xi^2, \quad (4.186)$$

where the dimensions of  $\xi$  are  $[\xi] = M^{1/2}L$  by convention. The Hamiltonian for this normal mode is then

$$\hat{H} = \frac{p^2}{2} + \frac{1}{2} \omega_0^2 \xi^2, \quad (4.187)$$

from which we see that both the kinetic as well as potential energy terms enter quadratically into the Hamiltonian. The classical rotational kinetic energy is also quadratic in the angular momentum components.

Let us compute the contribution of a single quadratic degree of freedom in  $\hat{H}$  to the partition function. We'll call this degree of freedom  $\zeta$  – it may be a position or momentum or angular momentum – and we'll write its contribution to  $\hat{H}$  as

$$\hat{H}_\zeta = \frac{1}{2} K \zeta^2, \quad (4.188)$$

where  $K$  is some constant. Integrating over  $\zeta$  yields the following factor in the partition function:

$$\int_{-\infty}^{\infty} d\zeta e^{-\beta K \zeta^2 / 2} = \left( \frac{2\pi}{K\beta} \right)^{1/2}. \quad (4.189)$$

The contribution to the Helmholtz free energy is then

$$\Delta F_\zeta = \frac{1}{2} k_B T \ln \left( \frac{K}{2\pi k_B T} \right), \quad (4.190)$$

and therefore the contribution to the internal energy  $E$  is

$$\Delta E_\zeta = \frac{\partial}{\partial \beta} (\beta \Delta F_\zeta) = \frac{1}{2\beta} = \frac{1}{2} k_B T. \quad (4.191)$$

We have thus derived what is commonly called the *equipartition theorem* of classical statistical mechanics:

*To each degree of freedom which enters the Hamiltonian quadratically is associated a contribution  $\frac{1}{2} k_B T$  to the internal energy of the system. This results in a concomitant contribution of  $\frac{1}{2} k_B$  to the heat capacity.*

We now see why the internal energy of a classical ideal gas with  $f$  degrees of freedom per molecule is  $E = \frac{1}{2} f N k_B T$ , and  $C_V = \frac{1}{2} N k_B$ . This result also has applications in the theory of solids. The atoms in a solid possess kinetic energy due to their motion, and potential energy due to the spring-like interatomic potentials which tend to keep the atoms in their preferred crystalline positions. Thus, for a three-dimensional crystal, there are *six* quadratic degrees of freedom (three positions and three momenta) per atom, and the classical energy should be  $E = 3N k_B T$ , and the heat capacity  $C_V = 3N k_B$ . As we shall see, quantum mechanics modifies this result considerably at temperatures below the highest normal mode (*i.e.* phonon) frequency, but the high temperature limit is given by the classical value  $C_V = 3\nu R$  (where  $\nu = N/N_A$  is the number of moles) derived here, known as the *Dulong-Petit limit*.

### 4.8.3 Quantum statistics and the Maxwell-Boltzmann limit

Consider a system composed of  $N$  noninteracting particles. The Hamiltonian is

$$\hat{H} = \sum_{j=1}^N \hat{h}_j. \quad (4.192)$$

The single particle Hamiltonian  $\hat{h}$  has eigenstates  $|\alpha\rangle$  with corresponding energy eigenvalues  $\varepsilon_\alpha$ . What is the partition function? Is it

$$H \stackrel{?}{=} \sum_{\alpha_1} \dots \sum_{\alpha_N} e^{-\beta(\varepsilon_{\alpha_1} + \varepsilon_{\alpha_2} + \dots + \varepsilon_{\alpha_N})} = \zeta^N, \quad (4.193)$$

where  $\zeta$  is the single particle partition function,

$$\zeta = \sum_{\alpha} e^{-\beta \varepsilon_{\alpha}} . \quad (4.194)$$

For systems where the individual particles are *distinguishable*, such as spins on a lattice which have fixed positions, this is indeed correct. But for particles free to move in a gas, this equation is *wrong*. The reason is that for *indistinguishable particles* the many particle quantum mechanical states are specified by a collection of *occupation numbers*  $n_{\alpha}$ , which tell us how many particles are in the single-particle state  $|\alpha\rangle$ . The energy is

$$E = \sum_{\alpha} n_{\alpha} \varepsilon_{\alpha} \quad (4.195)$$

and the total number of particles is

$$N = \sum_{\alpha} n_{\alpha} . \quad (4.196)$$

That is, each collection of occupation numbers  $\{n_{\alpha}\}$  labels a unique many particle state  $|\{n_{\alpha}\}\rangle$ . In the product  $\zeta^N$ , the collection  $\{n_{\alpha}\}$  occurs many times. We have therefore *overcounted* the contribution to  $Z_N$  due to this state. By what factor have we overcounted? It is easy to see that the overcounting factor is

$$\text{degree of overcounting} = \frac{N!}{\prod_{\alpha} n_{\alpha}!} ,$$

which is the number of ways we can rearrange the labels  $\alpha_j$  to arrive at the same collection  $\{n_{\alpha}\}$ . This follows from the multinomial theorem,

$$\left( \sum_{\alpha=1}^K x_{\alpha} \right)^N = \sum_{n_1} \sum_{n_2} \cdots \sum_{n_K} \frac{N!}{n_1! n_2! \cdots n_K!} x_1^{n_1} x_2^{n_2} \cdots x_K^{n_K} \delta_{N, n_1 + \dots + n_K} . \quad (4.197)$$

Thus, the correct expression for  $Z_N$  is

$$\begin{aligned} Z_N &= \sum_{\{n_{\alpha}\}} e^{-\beta \sum_{\alpha} n_{\alpha} \varepsilon_{\alpha}} \delta_{N, \sum_{\alpha} n_{\alpha}} \\ &= \sum_{\alpha_1} \sum_{\alpha_2} \cdots \sum_{\alpha_N} \left( \frac{\prod_{\alpha} n_{\alpha}!}{N!} \right) e^{-\beta(\varepsilon_{\alpha_1} + \varepsilon_{\alpha_2} + \dots + \varepsilon_{\alpha_N})} . \end{aligned} \quad (4.198)$$

When we study quantum statistics, we shall learn how to handle these constrained sums. For now it suffices to note that in the high temperature limit, almost all the  $n_{\alpha}$  are either 0 or 1, hence

$$Z_N \approx \frac{\zeta^N}{N!} . \quad (4.199)$$

This is the classical *Maxwell-Boltzmann limit* of quantum statistical mechanics. We now see the origin of the  $1/N!$  term which is so important in the thermodynamics of entropy of mixing.

## 4.9 Selected Examples

### 4.9.1 Spins in an external magnetic field

Consider a system of  $N_S$  spins, each of which can be either up ( $\sigma = +1$ ) or down ( $\sigma = -1$ ). The Hamiltonian for this system is

$$\hat{H} = -\mu_0 H \sum_{j=1}^{N_S} \sigma_j, \quad (4.200)$$

where now we write  $\hat{H}$  for the Hamiltonian, to distinguish it from the external magnetic field  $H$ , and  $\mu_0$  is the magnetic moment per particle. We treat this system within the ordinary canonical ensemble. The partition function is

$$Z = \sum_{\sigma_1} \cdots \sum_{\sigma_{N_S}} e^{-\beta \hat{H}} = \zeta^{N_S}, \quad (4.201)$$

where  $\zeta$  is the single particle partition function:

$$\zeta = \sum_{\sigma=\pm 1} e^{\mu_0 H \sigma / k_B T} = 2 \cosh\left(\frac{\mu_0 H}{k_B T}\right). \quad (4.202)$$

The Helmholtz free energy is then

$$F(T, H, N_S) = -k_B T \ln Z = -N_S k_B T \ln \left[ 2 \cosh\left(\frac{\mu_0 H}{k_B T}\right) \right]. \quad (4.203)$$

The magnetization is

$$M = -\left(\frac{\partial F}{\partial H}\right)_{T, N_S} = N_S \mu_0 \tanh\left(\frac{\mu_0 H}{k_B T}\right). \quad (4.204)$$

The energy is

$$E = \frac{\partial}{\partial \beta} (\beta F) = -N_S \mu_0 H \tanh\left(\frac{\mu_0 H}{k_B T}\right). \quad (4.205)$$

Hence,  $E = -HM$ , which we already knew, from the form of  $\hat{H}$  itself.

Each spin here is independent. The probability that a given spin has polarization  $\sigma$  is

$$P_\sigma = \frac{e^{\beta \mu_0 H \sigma}}{e^{\beta \mu_0 H} + e^{-\beta \mu_0 H}}. \quad (4.206)$$

The total probability is unity, and the average polarization is a weighted average of  $\sigma = +1$  and  $\sigma = -1$  contributions:

$$P_\uparrow + P_\downarrow = 1, \quad \langle \sigma \rangle = P_\uparrow - P_\downarrow = \tanh\left(\frac{\mu_0 H}{k_B T}\right). \quad (4.207)$$

At low temperatures  $T \ll \mu_0 H / k_B$ , we have  $P_\uparrow \approx 1 - e^{-2\mu_0 H / k_B T}$ . At high temperatures  $T > \mu_0 H / k_B$ , the two polarizations are equally likely, and  $P_\sigma \approx \frac{1}{2} \left(1 + \frac{\sigma \mu_0 H}{k_B T}\right)$ .

The *isothermal magnetic susceptibility* is defined as

$$\chi_T = \frac{1}{N_S} \left( \frac{\partial M}{\partial H} \right)_T = \frac{\mu_0^2}{k_B T} \operatorname{sech}^2 \left( \frac{\mu_0 H}{k_B T} \right). \quad (4.208)$$

(Typically this is computed per unit volume rather than per particle.) At  $H = 0$ , we have  $\chi_T = \mu_0^2/k_B T$ , which is known as the *Curie law*.

### Aside

The energy  $E = -HM$  here is not the same quantity we discussed in our study of thermodynamics. In fact, the thermodynamic energy for this problem vanishes! Here is why. To avoid confusion, we'll need to invoke a new symbol for the thermodynamic energy,  $\mathcal{E}$ . Recall that the thermodynamic energy  $\mathcal{E}$  is a function of extensive quantities, meaning  $\mathcal{E} = \mathcal{E}(S, M, N_S)$ . It is obtained from the free energy  $F(T, H, N_S)$  by a double Legendre transform:

$$\mathcal{E}(S, M, N_S) = F(T, H, N_S) + TS + HM. \quad (4.209)$$

Now from eqn. 4.203 we derive the entropy

$$S = -\frac{\partial F}{\partial T} = N_S k_B \ln \left[ 2 \cosh \left( \frac{\mu_0 H}{k_B T} \right) \right] - N_S \frac{\mu_0 H}{T} \tanh \left( \frac{\mu_0 H}{k_B T} \right). \quad (4.210)$$

Thus, using eqns. 4.203 and 4.204, we obtain  $\mathcal{E}(S, M, N_S) = 0$ .

The potential confusion here arises from our use of the expression  $F(T, H, N_S)$ . In thermodynamics, it is the Gibbs free energy  $G(T, p, N)$  which is a double Legendre transform of the energy:  $G = \mathcal{E} - TS + pV$ . By analogy, with magnetic systems we should perhaps write  $G = \mathcal{E} - TS - HM$ , but in keeping with many textbooks we shall use the symbol  $F$  and refer to it as the Helmholtz free energy. The quantity we've called  $E$  in eqn. 4.205 is in fact  $E = \mathcal{E} - HM$ , which means  $\mathcal{E} = 0$ . The energy  $\mathcal{E}(S, M, N_S)$  vanishes here because the spins are noninteracting.

### 4.9.2 Negative temperature (!)

Consider again a system of  $N_S$  spins, each of which can be either up (+) or down (-). Let  $N_\sigma$  be the number of sites with spin  $\sigma$ , where  $\sigma = \pm 1$ . Clearly  $N_+ + N_- = N_S$ . We now treat this system within the microcanonical ensemble.

The energy of the system is

$$E = -HM, \quad (4.211)$$

where  $H$  is an external magnetic field, and  $M = (N_+ - N_-) \mu_0$  is the total magnetization. We now compute  $S(E)$  using the ordinary canonical ensemble. The number of ways of arranging the system with  $N_+$  up spins is

$$\Omega = \binom{N_S}{N_+}, \quad (4.212)$$

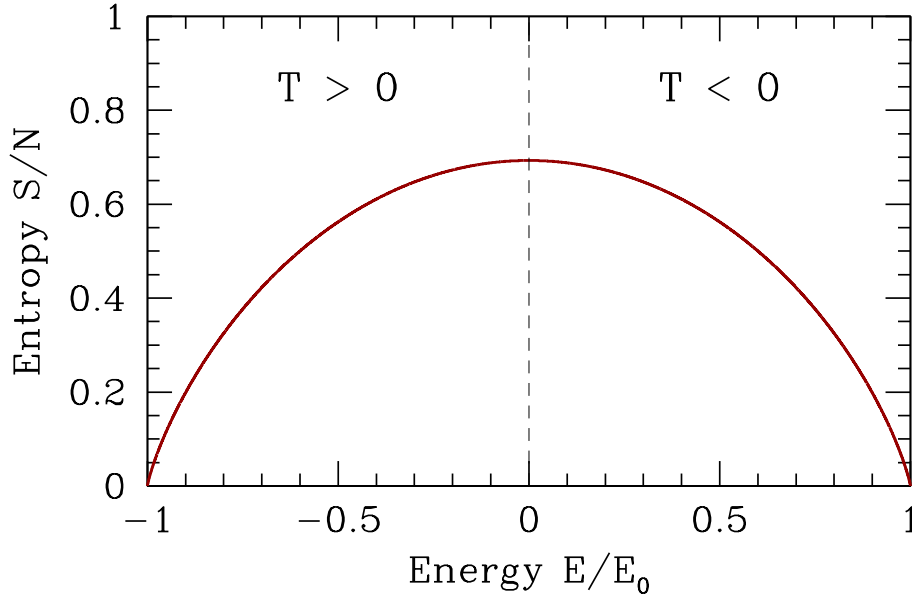


Figure 4.7: When entropy decreases with increasing energy, the temperature is negative. Typically, kinetic degrees of freedom prevent this peculiarity from manifesting in physical systems.

hence the entropy is

$$S = k_B \ln \Omega = -N_S k_B \left\{ x \ln x + (1-x) \ln(1-x) \right\} \quad (4.213)$$

in the thermodynamic limit:  $N_S \rightarrow \infty$ ,  $N_+ \rightarrow \infty$ ,  $x = N_+/N_S$  constant. Now the magnetization is  $M = (N_+ - N_-)\mu_0 = (2N_+ - N_S)\mu_0$ , hence if we define the maximum energy  $E_0 \equiv N_S \mu_0 H$ , then

$$\frac{E}{E_0} = -\frac{M}{N_S \mu_0} = 1 - 2x \quad \implies \quad x = \frac{E_0 - E}{2E_0}. \quad (4.214)$$

We therefore have

$$S(E, N_S) = -N_S k_B \left[ \left( \frac{E_0 - E}{2E_0} \right) \ln \left( \frac{E_0 - E}{2E_0} \right) + \left( \frac{E_0 + E}{2E_0} \right) \ln \left( \frac{E_0 + E}{2E_0} \right) \right]. \quad (4.215)$$

We now have

$$\frac{1}{T} = \left( \frac{\partial S}{\partial E} \right)_{N_S} = \frac{\partial S}{\partial x} \frac{\partial x}{\partial E} = \frac{N_S k_B}{2E_0} \ln \left( \frac{E_0 - E}{E_0 + E} \right). \quad (4.216)$$

We see that the temperature is positive for  $-E_0 \leq E < 0$  and is *negative* for  $0 < E \leq E_0$ .

What has gone wrong? The answer is that *nothing* has gone wrong – all our calculations are perfectly correct. This system *does* exhibit the possibility of negative temperature. It is, however, unphysical in that we have neglected kinetic degrees of freedom, which result in an entropy function  $S(E, N_S)$  which is an increasing function of energy. In this system,  $S(E, N_S)$  achieves a maximum of  $S_{\max} = N_S k_B \ln 2$  at  $E = 0$  (i.e.  $x = \frac{1}{2}$ ), and then turns over and starts decreasing. In fact, our results are completely consistent with eqn. 4.205 : the energy  $E$  is an odd function of temperature. Positive energy requires negative temperature! Another example of this peculiarity is provided in the appendix in §4.11.2.

### 4.9.3 Adsorption

PROBLEM: A surface containing  $N_S$  adsorption sites is in equilibrium with a monatomic ideal gas. Atoms adsorbed on the surface have an energy  $-\Delta$  and no kinetic energy. Each adsorption site can accommodate at most one atom. Calculate the fraction  $f$  of occupied adsorption sites as a function of the gas density  $n$ , the temperature  $T$ , the binding energy  $\Delta$ , and physical constants.

The grand partition function for the surface is

$$\begin{aligned}\Xi_{\text{surf}} &= e^{-\Omega_{\text{surf}}/k_B T} = \sum_{j=0}^{N_S} \binom{N_S}{j} e^{j(\mu+\Delta)/k_B T} \\ &= (1 + e^{\mu/k_B T} e^{\Delta/k_B T})^{N_S}.\end{aligned}\quad (4.217)$$

The fraction of occupied sites is

$$f = \frac{\langle \hat{N}_{\text{surf}} \rangle}{N_S} = -\frac{1}{N_S} \frac{\partial \Omega_{\text{surf}}}{\partial \mu} = \frac{e^{\mu/k_B T}}{e^{\mu/k_B T} + e^{-\Delta/k_B T}}.\quad (4.218)$$

Since the surface is in equilibrium with the gas, its fugacity  $z = \exp(\mu/k_B T)$  and temperature  $T$  are the same as in the gas.

SOLUTION: For a monatomic ideal gas, the single particle partition function is  $\zeta = V\lambda_T^{-3}$ , where  $\lambda_T = \sqrt{2\pi\hbar^2/mk_B T}$  is the thermal wavelength. Thus, the grand partition function, for indistinguishable particles, is

$$\Xi_{\text{gas}} = \exp\left(V\lambda_T^{-3} e^{\mu/k_B T}\right).\quad (4.219)$$

The gas density is

$$n = \frac{\langle \hat{N}_{\text{gas}} \rangle}{V} = -\frac{1}{V} \frac{\partial \Omega_{\text{gas}}}{\partial \mu} = \lambda_T^{-3} e^{\mu/k_B T}.\quad (4.220)$$

We can now solve for the fugacity:  $z = e^{\mu/k_B T} = n\lambda_T^3$ . Thus, the fraction of occupied adsorption sites is

$$f = \frac{n\lambda_T^3}{n\lambda_T^3 + e^{-\Delta/k_B T}}.\quad (4.221)$$

Interestingly, the solution for  $f$  involves the constant  $\hbar$ .

It is always advisable to check that the solution makes sense in various limits. First of all, if the gas density tends to zero at fixed  $T$  and  $\Delta$ , we have  $f \rightarrow 0$ . On the other hand, if  $n \rightarrow \infty$  we have  $f \rightarrow 1$ , which also makes sense. At fixed  $n$  and  $T$ , if the adsorption energy is  $(-\Delta) \rightarrow -\infty$ , then once again  $f = 1$  since every adsorption site wants to be occupied. Conversely, taking  $(-\Delta) \rightarrow +\infty$  results in  $n \rightarrow 0$ , since the energetic cost of adsorption is infinitely high.

### 4.9.4 Elasticity of wool

Wool consists of interlocking protein molecules which can stretch into an elongated configuration, but reversibly so. This feature gives wool its very useful elasticity. Let us model a chain of these proteins

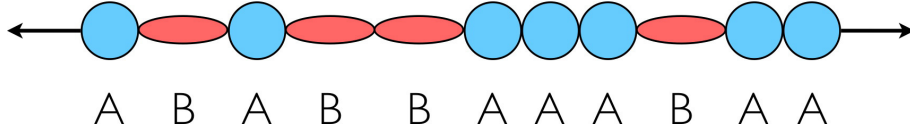


Figure 4.8: The monomers in wool are modeled as existing in one of two states. The low energy undeformed state is A, and the higher energy deformed state is B. Applying tension induces more monomers to enter the B state.

by assuming they can exist in one of two states, which we will call A and B, with energies  $\varepsilon_A$  and  $\varepsilon_B$  and lengths  $\ell_A$  and  $\ell_B$ . The situation is depicted in fig. 4.8. We model these conformational degrees of freedom by a spin variable  $\sigma = \pm 1$  for each molecule, where  $\sigma = +1$  in the A state and  $\sigma = -1$  in the B state. Suppose a chain consisting of  $N$  monomers is placed under a tension  $\tau$ . We then have

$$\hat{H} = \sum_{j=1}^N \left[ \varepsilon_A \delta_{\sigma_j, +1} + \varepsilon_B \delta_{\sigma_j, -1} \right]. \quad (4.222)$$

Similarly, the length is

$$\hat{L} = \sum_{j=1}^N \left[ \ell_A \delta_{\sigma_j, +1} + \ell_B \delta_{\sigma_j, -1} \right]. \quad (4.223)$$

The Gibbs partition function is  $Y = \text{Tr} e^{-\hat{K}/k_B T}$ , with  $\hat{K} = \hat{H} - \tau \hat{L}$ :

$$\hat{K} = \sum_{j=1}^N \left[ \tilde{\varepsilon}_A \delta_{\sigma_j, +1} + \tilde{\varepsilon}_B \delta_{\sigma_j, -1} \right], \quad (4.224)$$

where  $\tilde{\varepsilon}_A \equiv \varepsilon_A - \tau \ell_A$  and  $\tilde{\varepsilon}_B \equiv \varepsilon_B - \tau \ell_B$ . At  $\tau = 0$  the A state is preferred for each monomer, but when  $\tau$  exceeds  $\tau^*$ , defined by the relation  $\tilde{\varepsilon}_A = \tilde{\varepsilon}_B$ , the B state is preferred. One finds

$$\tau^* = \frac{\varepsilon_B - \varepsilon_A}{\ell_B - \ell_A}. \quad (4.225)$$

Once again, we have a set of  $N$  noninteracting spins. The partition function is  $Y = \zeta^N$ , where  $\zeta$  is the single monomer partition function,  $\zeta = \text{Tr} e^{-\beta \hat{h}}$ , where

$$\hat{h} = \tilde{\varepsilon}_A \delta_{\sigma_j, 1} + \tilde{\varepsilon}_B \delta_{\sigma_j, -1} \quad (4.226)$$

is the single “spin” Hamiltonian. Thus,

$$\zeta = \text{Tr} e^{-\beta \hat{h}} = e^{-\beta \tilde{\varepsilon}_A} + e^{-\beta \tilde{\varepsilon}_B}, \quad (4.227)$$

It is convenient to define the differences

$$\Delta \varepsilon = \varepsilon_B - \varepsilon_A, \quad \Delta \ell = \ell_B - \ell_A, \quad \Delta \tilde{\varepsilon} = \tilde{\varepsilon}_B - \tilde{\varepsilon}_A \quad (4.228)$$



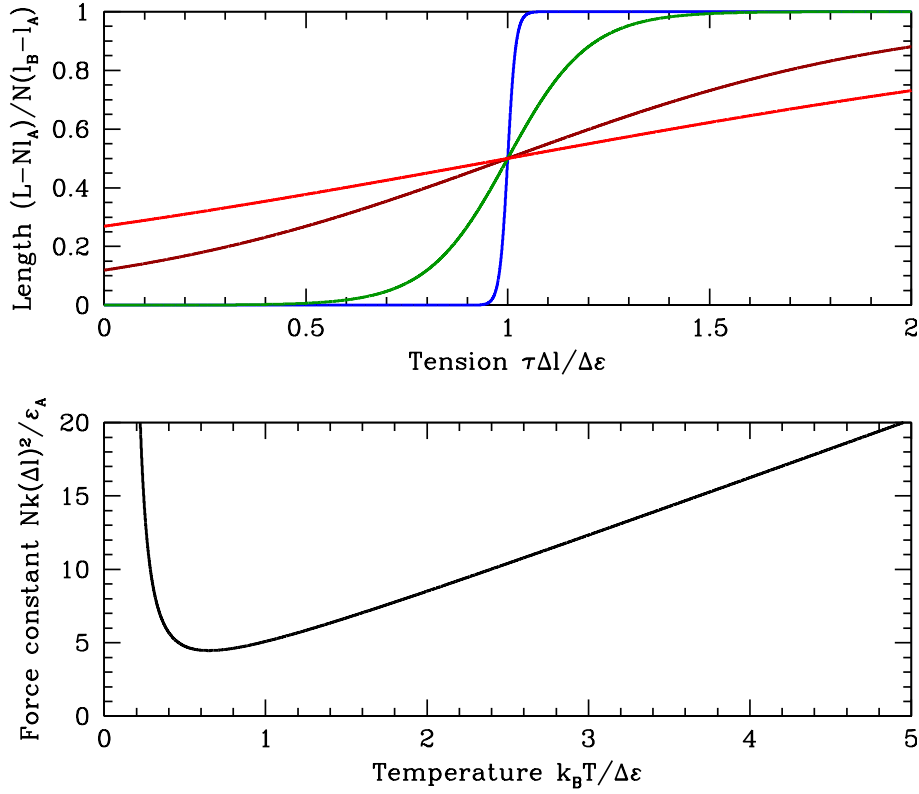


Figure 4.9: Upper panel: length  $L(\tau, T)$  for  $k_B T / \tilde{\epsilon} = 0.01$  (blue), 0.1 (green), 0.5 (dark red), and 1.0 (red). Bottom panel: dimensionless force constant  $k/N(\Delta\ell)^2$  versus temperature.

in which case the partition function  $Y$  is

$$Y(T, \tau, N) = e^{-N\beta\tilde{\epsilon}_A} \left[ 1 + e^{-\beta\Delta\tilde{\epsilon}} \right]^N \quad (4.229)$$

$$G(T, \tau, N) = N\tilde{\epsilon}_A - Nk_B T \ln \left[ 1 + e^{-\Delta\tilde{\epsilon}/k_B T} \right] \quad (4.230)$$

The average length is

$$\begin{aligned} L = \langle \hat{L} \rangle &= - \left( \frac{\partial G}{\partial \tau} \right)_{T, N} \\ &= N\ell_A + \frac{N\Delta\ell}{e^{(\Delta\epsilon - \tau\Delta\ell)/k_B T} + 1}. \end{aligned} \quad (4.231)$$

The polymer behaves as a spring, and for small  $\tau$  the spring constant is

$$k = \left. \frac{\partial \tau}{\partial L} \right|_{\tau=0} = \frac{4k_B T}{N(\Delta\ell)^2} \cosh^2 \left( \frac{\Delta\epsilon}{2k_B T} \right). \quad (4.232)$$

The results are shown in fig. 4.9. Note that length increases with temperature for  $\tau < \tau^*$  and decreases with temperature for  $\tau > \tau^*$ . Note also that  $k$  diverges at both low and high temperatures. At low  $T$ , the energy gap  $\Delta\epsilon$  dominates and  $L = N\ell_A$ , while at high temperatures  $k_B T$  dominates and  $L = \frac{1}{2}N(\ell_A + \ell_B)$ .

### 4.9.5 Noninteracting spin dimers

Consider a system of noninteracting spin dimers as depicted in fig. 4.10. Each dimer contains two spins, and is described by the Hamiltonian

$$\hat{H}_{\text{dimer}} = -J \sigma_1 \sigma_2 - \mu_0 H (\sigma_1 + \sigma_2). \quad (4.233)$$

Here,  $J$  is an *interaction energy* between the spins which comprise the dimer. If  $J > 0$  the interaction is *ferromagnetic*, which prefers that the spins are aligned. That is, the lowest energy states are  $|\uparrow\uparrow\rangle$  and  $|\downarrow\downarrow\rangle$ . If  $J < 0$  the interaction is *antiferromagnetic*, which prefers that spins be anti-aligned:  $|\uparrow\downarrow\rangle$  and  $|\downarrow\uparrow\rangle$ .<sup>6</sup>

Suppose there are  $N_d$  dimers. Then the OCE partition function is  $Z = \zeta^{N_d}$ , where  $\zeta(T, H)$  is the single dimer partition function. To obtain  $\zeta(T, H)$ , we sum over the four possible states of the two spins, obtaining

$$\begin{aligned} \zeta &= \text{Tr} e^{-\hat{H}_{\text{dimer}}/k_B T} \\ &= 2 e^{-J/k_B T} + 2 e^{J/k_B T} \cosh\left(\frac{2\mu_0 H}{k_B T}\right). \end{aligned}$$

Thus, the free energy is

$$F(T, H, N_d) = -N_d k_B T \ln 2 - N_d k_B T \ln \left[ e^{-J/k_B T} + e^{J/k_B T} \cosh\left(\frac{2\mu_0 H}{k_B T}\right) \right]. \quad (4.234)$$

The magnetization is

$$M = - \left( \frac{\partial F}{\partial H} \right)_{T, N_d} = 2N_d \mu_0 \cdot \frac{e^{J/k_B T} \sinh\left(\frac{2\mu_0 H}{k_B T}\right)}{e^{-J/k_B T} + e^{J/k_B T} \cosh\left(\frac{2\mu_0 H}{k_B T}\right)} \quad (4.235)$$

It is instructive to consider the zero field isothermal susceptibility per spin,

$$\chi_T = \frac{1}{2N_d} \left. \frac{\partial M}{\partial H} \right|_{H=0} = \frac{\mu_0^2}{k_B T} \cdot \frac{2 e^{J/k_B T}}{e^{J/k_B T} + e^{-J/k_B T}}. \quad (4.236)$$

The quantity  $\mu_0^2/k_B T$  is simply the Curie susceptibility for noninteracting classical spins. Note that we correctly recover the Curie result when  $J = 0$ , since then the individual spins comprising each dimer are in fact noninteracting. For the ferromagnetic case, if  $J \gg k_B T$ , then we obtain

$$\chi_T(J \gg k_B T) \approx \frac{2\mu_0^2}{k_B T}. \quad (4.237)$$

This has the following simple interpretation. When  $J \gg k_B T$ , the spins of each dimer are effectively locked in parallel. Thus, each dimer has an effective magnetic moment  $\mu_{\text{eff}} = 2\mu_0$ . On the other hand, there are only half as many dimers as there are spins, so the resulting Curie susceptibility per spin is  $\frac{1}{2} \times (2\mu_0)^2/k_B T$ .

<sup>6</sup>Nota bene we are concerned with classical spin configurations only – there is no superposition of states allowed in this model!

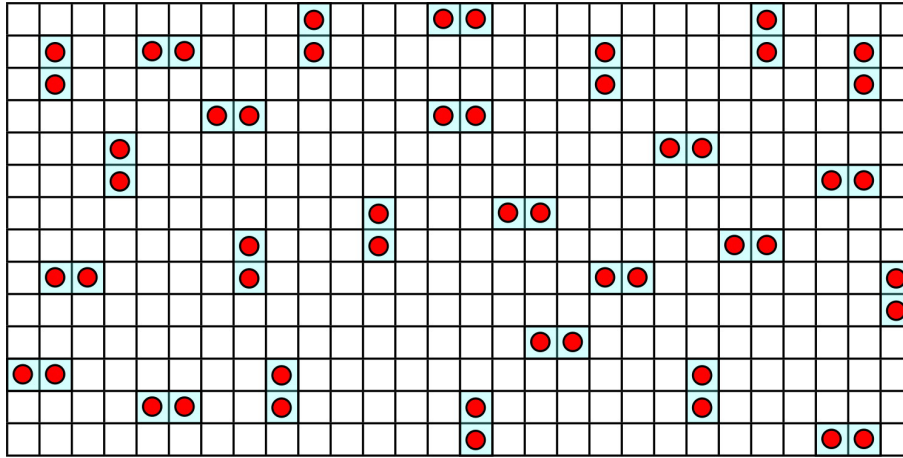


Figure 4.10: A model of noninteracting spin dimers on a lattice. Each red dot represents a classical spin for which  $\sigma_j = \pm 1$ .

When  $-J \gg k_B T$ , the spins of each dimer are effectively locked in one of the two antiparallel configurations. We then have

$$\chi_T(-J \gg k_B T) \approx \frac{2\mu_0^2}{k_B T} e^{-2|J|/k_B T}. \quad (4.238)$$

In this case, the individual dimers have essentially zero magnetic moment.

## 4.10 Statistical Mechanics of Molecular Gases

### 4.10.1 Separation of translational and internal degrees of freedom

The states of a noninteracting atom or molecule are labeled by its total momentum  $\mathbf{p}$  and its internal quantum numbers, which we will simply write with a collective index  $\alpha$ , specifying rotational, vibrational, and electronic degrees of freedom. The single particle Hamiltonian is then

$$\hat{h} = \frac{\mathbf{p}^2}{2m} + \hat{h}_{\text{int}}, \quad (4.239)$$

with

$$\hat{h} |\mathbf{k}, \alpha\rangle = \left( \frac{\hbar^2 \mathbf{k}^2}{2m} + \varepsilon_\alpha \right) |\mathbf{k}, \alpha\rangle. \quad (4.240)$$

The partition function is

$$\zeta = \text{Tr} e^{-\beta \hat{h}} = \sum_{\mathbf{p}} e^{-\beta \mathbf{p}^2 / 2m} \sum_j g_j e^{-\beta \varepsilon_j}. \quad (4.241)$$

Here we have replaced the internal label  $\alpha$  with a label  $j$  of energy eigenvalues, with  $g_j$  being the degeneracy of the internal state with energy  $\varepsilon_j$ . To do the  $\mathbf{p}$  sum, we quantize in a box of dimensions

$L_1 \times L_2 \times \cdots \times L_d$ , using periodic boundary conditions. Then

$$\mathbf{p} = \left( \frac{2\pi\hbar n_1}{L_1}, \frac{2\pi\hbar n_2}{L_2}, \dots, \frac{2\pi\hbar n_d}{L_d} \right), \quad (4.242)$$

where each  $n_i$  is an integer. Since the differences between neighboring quantized  $\mathbf{p}$  vectors are very tiny, we can replace the sum over  $\mathbf{p}$  by an integral:

$$\sum_{\mathbf{p}} \rightarrow \int \frac{d^d p}{\Delta p_1 \cdots \Delta p_d} \quad (4.243)$$

where the volume in momentum space of an elementary rectangle is

$$\Delta p_1 \cdots \Delta p_d = \frac{(2\pi\hbar)^d}{L_1 \cdots L_d} = \frac{(2\pi\hbar)^d}{V}. \quad (4.244)$$

Thus,

$$\zeta = V \int \frac{d^d p}{(2\pi\hbar)^d} e^{-p^2/2mk_B T} \sum_j g_j e^{-\varepsilon_j/k_B T} = V \lambda_T^{-d} \xi \quad (4.245)$$

$$\xi(T) = \sum_j g_j e^{-\varepsilon_j/k_B T}. \quad (4.246)$$

Here,  $\xi(T)$  is the *internal coordinate partition function*. The full  $N$ -particle ordinary canonical partition function is then

$$Z_N = \frac{1}{N!} \left( \frac{V}{\lambda_T^d} \right)^N \xi^N(T). \quad (4.247)$$

Using Stirling's approximation, we find the Helmholtz free energy  $F = -k_B T \ln Z$  is

$$\begin{aligned} F(T, V, N) &= -Nk_B T \left[ \ln \left( \frac{V}{N\lambda_T^d} \right) + 1 + \ln \xi(T) \right] \\ &= -Nk_B T \left[ \ln \left( \frac{V}{N\lambda_T^d} \right) + 1 \right] + N\varphi(T), \end{aligned} \quad (4.248)$$

where

$$\varphi(T) = -k_B T \ln \xi(T) \quad (4.249)$$

is the internal coordinate contribution to the single particle free energy. We could also compute the partition function in the Gibbs  $(T, p, N)$  ensemble:

$$\begin{aligned} Y(T, p, N) &= e^{-\beta G(T, p, N)} = \frac{1}{V_0} \int_0^\infty dV e^{-\beta p V} Z(T, V, N) \\ &= \left( \frac{k_B T}{p V_0} \right) \left( \frac{k_B T}{p \lambda_T^d} \right)^N \xi^N(T). \end{aligned} \quad (4.250)$$

Thus, in the thermodynamic limit,

$$\begin{aligned}\mu(T, p) &= \frac{G(T, p, N)}{N} = k_B T \ln \left( \frac{p \lambda_T^d}{k_B T} \right) - k_B T \ln \xi(T) \\ &= k_B T \ln \left( \frac{p \lambda_T^d}{k_B T} \right) + \varphi(T).\end{aligned}\quad (4.251)$$

### 4.10.2 Ideal gas law

Since the internal coordinate contribution to the free energy is volume-independent, we have

$$V = \left( \frac{\partial G}{\partial p} \right)_{T, N} = \frac{N k_B T}{p}, \quad (4.252)$$

and the ideal gas law applies. The entropy is

$$S = - \left( \frac{\partial G}{\partial T} \right)_{p, N} = N k_B \left[ \ln \left( \frac{k_B T}{p \lambda_T^d} \right) + 1 + \frac{1}{2} d \right] - N \varphi'(T), \quad (4.253)$$

and therefore the heat capacity is

$$C_p = T \left( \frac{\partial S}{\partial T} \right)_{p, N} = \left( \frac{1}{2} d + 1 \right) N k_B - N T \varphi''(T) \quad (4.254)$$

$$C_V = T \left( \frac{\partial S}{\partial T} \right)_{V, N} = \frac{1}{2} d N k_B - N T \varphi''(T). \quad (4.255)$$

Thus, any temperature variation in  $C_p$  must be due to the internal degrees of freedom.

### 4.10.3 The internal coordinate partition function

At energy scales of interest we can separate the internal degrees of freedom into distinct classes, writing

$$\hat{h}_{\text{int}} = \hat{h}_{\text{rot}} + \hat{h}_{\text{vib}} + \hat{h}_{\text{elec}} \quad (4.256)$$

as a sum over internal Hamiltonians governing rotational, vibrational, and electronic degrees of freedom. Then

$$\xi_{\text{int}} = \xi_{\text{rot}} \cdot \xi_{\text{vib}} \cdot \xi_{\text{elec}}. \quad (4.257)$$

Associated with each class of excitation is a characteristic temperature  $\Theta$ . Rotational and vibrational temperatures of a few common molecules are listed in table 4.1.

molecule	$\Theta_{\text{rot}}(\text{K})$	$\Theta_{\text{vib}}(\text{K})$
H <sub>2</sub>	85.4	6100
N <sub>2</sub>	2.86	3340
H <sub>2</sub> O	13.7, 21.0, 39.4	2290, 5180, 5400

Table 4.1: Some rotational and vibrational temperatures of common molecules.

#### 4.10.4 Rotations

Consider a class of molecules which can be approximated as an axisymmetric top. The rotational Hamiltonian is then

$$\begin{aligned}\hat{h}_{\text{rot}} &= \frac{L_a^2 + L_b^2}{2I_1} + \frac{L_c^2}{2I_3} \\ &= \frac{\hbar^2 L(L+1)}{2I_1} + \left( \frac{1}{2I_3} - \frac{1}{2I_1} \right) L_c^2,\end{aligned}\quad (4.258)$$

where  $\hat{n}_{a,b,c}(t)$  are the principal axes, with  $\hat{n}_c$  the symmetry axis, and  $L_{a,b,c}$  are the components of the angular momentum vector  $\mathbf{L}$  about these instantaneous body-fixed principal axes. The components of  $\mathbf{L}$  along *space-fixed* axes  $\{x, y, z\}$  are written as  $L^{x,y,z}$ . Note that

$$[L^\mu, L_c] = n_c^\nu [L^\mu, L^\nu] + [L^\mu, n_c^\nu] L^\nu = i\epsilon_{\mu\nu\lambda} n_c^\nu L^\lambda + i\epsilon_{\mu\nu\lambda} n_c^\lambda L^\nu = 0, \quad (4.259)$$

which is equivalent to the statement that  $L_c = \hat{n}_c \cdot \mathbf{L}$  is a rotational scalar. We can therefore simultaneously specify the eigenvalues of  $\{L^2, L^z, L_c\}$ , which form a complete set of commuting observables (CSCO)<sup>7</sup>. The eigenvalues of  $L^z$  are  $m\hbar$  with  $m \in \{-L, \dots, L\}$ , while those of  $L_c$  are  $k\hbar$  with  $k \in \{-L, \dots, L\}$ . There is a  $(2L+1)$ -fold degeneracy associated with the  $L^z$  quantum number.

We assume the molecule is prolate, so that  $I_3 < I_1$ . We can then define two temperature scales,

$$\Theta = \frac{\hbar^2}{2I_1 k_B}, \quad \tilde{\Theta} = \frac{\hbar^2}{2I_3 k_B}. \quad (4.260)$$

Prolateness then means  $\tilde{\Theta} > \Theta$ . We conclude that the rotational partition function for an axisymmetric molecule is given by

$$\xi_{\text{rot}}(T) = \sum_{L=0}^{\infty} (2L+1) e^{-L(L+1)\Theta/T} \sum_{k=-L}^L e^{-k^2(\tilde{\Theta}-\Theta)/T} \quad (4.261)$$

In diatomic molecules,  $I_3$  is extremely small, and  $\tilde{\Theta} \gg k_B T$  at all relevant temperatures. Only the  $k=0$  term contributes to the partition sum, and we have

$$\xi_{\text{rot}}(T) = \sum_{L=0}^{\infty} (2L+1) e^{-L(L+1)\Theta/T}. \quad (4.262)$$

<sup>7</sup>Note that while we cannot simultaneously specify the eigenvalues of two components of  $\mathbf{L}$  along axes fixed in space, we can simultaneously specify the components of  $\mathbf{L}$  along one axis fixed in space and one axis rotating with a body. See Landau and Lifshitz, *Quantum Mechanics*, §103.

When  $T \ll \Theta$ , only the first few terms contribute, and

$$\xi_{\text{rot}}(T) = 1 + 3e^{-2\Theta/T} + 5e^{-6\Theta/T} + \dots \quad (4.263)$$

In the high temperature limit, we have a slowly varying summand. The *Euler-MacLaurin summation formula* may be used to evaluate such a series:

$$\sum_{k=0}^n F_k = \int_0^n dk F(k) + \frac{1}{2}[F(0) + F(n)] + \sum_{j=1}^{\infty} \frac{B_{2j}}{(2j)!} [F^{(2j-1)}(n) - F^{(2j-1)}(0)] \quad (4.264)$$

where  $B_j$  is the  $j^{\text{th}}$  Bernoulli number where

$$B_0 = 1 \quad , \quad B_1 = -\frac{1}{2} \quad , \quad B_2 = \frac{1}{6} \quad , \quad B_4 = -\frac{1}{30} \quad , \quad B_6 = \frac{1}{42} \quad . \quad (4.265)$$

Thus,

$$\sum_{k=0}^{\infty} F_k = \int_0^{\infty} dx F(x) + \frac{1}{2}F(0) - \frac{1}{12}F'(0) - \frac{1}{720}F'''(0) + \dots \quad (4.266)$$

We have  $F(x) = (2x+1)e^{-x(x+1)\Theta/T}$ , for which  $\int_0^{\infty} dx F(x) = \frac{T}{\Theta}$ , hence

$$\xi_{\text{rot}} = \frac{T}{\Theta} + \frac{1}{3} + \frac{1}{15} \frac{\Theta}{T} + \frac{4}{315} \left(\frac{\Theta}{T}\right)^2 + \dots \quad (4.267)$$

Recall that  $\varphi(T) = -k_B T \ln \xi(T)$ . We conclude that  $\varphi_{\text{rot}}(T) \approx -3k_B T e^{-2\Theta/T}$  for  $T \ll \Theta$  and  $\varphi_{\text{rot}}(T) \approx -k_B T \ln(T/\Theta)$  for  $T \gg \Theta$ . We have seen that the internal coordinate contribution to the heat capacity is  $\Delta C_V = -NT\varphi''(T)$ . For diatomic molecules, then, this contribution is exponentially suppressed for  $T \ll \Theta$ , while for high temperatures we have  $\Delta C_V = Nk_B$ . One says that the rotational excitations are 'frozen out' at temperatures much below  $\Theta$ . Including the first few terms, we have

$$\Delta C_V(T \ll \Theta) = 12 Nk_B \left(\frac{\Theta}{T}\right)^2 e^{-2\Theta/T} + \dots \quad (4.268)$$

$$\Delta C_V(T \gg \Theta) = Nk_B \left\{ 1 + \frac{1}{45} \left(\frac{\Theta}{T}\right)^2 + \frac{16}{945} \left(\frac{\Theta}{T}\right)^3 + \dots \right\} \quad (4.269)$$

Note that  $C_V$  overshoots its limiting value of  $Nk_B$  and asymptotically approaches it from above.

Special care must be taken in the case of homonuclear diatomic molecules, for then only even or odd  $L$  states are allowed, depending on the total nuclear spin. This is discussed below in §4.10.7.

For polyatomic molecules, the moments of inertia generally are large enough that the molecule's rotations can be considered classically. We then have

$$\varepsilon(L_a, L_b, L_c) = \frac{L_a^2}{2I_1} + \frac{L_b^2}{2I_2} + \frac{L_c^2}{2I_3} \quad (4.270)$$

We then have

$$\xi_{\text{rot}}(T) = \frac{1}{g_{\text{rot}}} \int \frac{dL_a dL_b dL_c d\phi d\theta d\psi}{(2\pi\hbar)^3} e^{-\varepsilon(L_a L_b L_c)/k_B T}, \quad (4.271)$$

where  $(\phi, \theta, \psi)$  are the Euler angles. Recall  $\phi \in [0, 2\pi]$ ,  $\theta \in [0, \pi]$ , and  $\psi \in [0, 2\pi]$ . The factor  $g_{\text{rot}}$  accounts for physically indistinguishable orientations of the molecule brought about by rotations, which can happen when more than one of the nuclei is the same. We then have

$$\xi_{\text{rot}}(T) = \left( \frac{2k_B T}{\hbar^2} \right)^{3/2} \sqrt{\pi I_1 I_2 I_3}. \quad (4.272)$$

This leads to  $\Delta C_V = \frac{3}{2} N k_B$ .

#### 4.10.5 Vibrations

Vibrational frequencies are often given in units of inverse wavelength, such as  $\text{cm}^{-1}$ , called a *wavenumber*. To convert to a temperature scale  $T^*$ , we write  $k_B T^* = h\nu = hc/\lambda$ , hence  $T^* = (hc/k_B) \lambda^{-1}$ , and we multiply by

$$\frac{hc}{k_B} = 1.436 \text{ K} \cdot \text{cm}. \quad (4.273)$$

For example, infrared absorption ( $\sim 50 \text{ cm}^{-1}$  to  $10^4 \text{ cm}^{-1}$ ) reveals that the ‘asymmetric stretch’ mode of the  $\text{H}_2\text{O}$  molecule has a vibrational frequency of  $\nu = 3756 \text{ cm}^{-1}$ . The corresponding temperature scale is  $T^* = 5394 \text{ K}$ .

Vibrations are normal modes of oscillations. A single normal mode Hamiltonian is of the form

$$\hat{h} = \frac{p^2}{2m} + \frac{1}{2} m \omega^2 q^2 = \hbar \omega \left( a^\dagger a + \frac{1}{2} \right). \quad (4.274)$$

In general there are many vibrational modes, hence many normal mode frequencies  $\omega_\alpha$ . We then must sum over all of them, resulting in

$$\xi_{\text{vib}} = \prod_{\alpha} \xi_{\text{vib}}^{(\alpha)}. \quad (4.275)$$

For each such normal mode, the contribution is

$$\begin{aligned} \xi &= \sum_{n=0}^{\infty} e^{-(n+\frac{1}{2})\hbar\omega/k_B T} = e^{-\hbar\omega/2k_B T} \sum_{n=0}^{\infty} \left( e^{-\hbar\omega/k_B T} \right)^n \\ &= \frac{e^{-\hbar\omega/2k_B T}}{1 - e^{-\hbar\omega/k_B T}} = \frac{1}{2 \sinh(\Theta/2T)}, \end{aligned} \quad (4.276)$$

where  $\Theta = \hbar\omega/k_B$ . Then

$$\begin{aligned} \varphi &= k_B T \ln \left( 2 \sinh(\Theta/2T) \right) \\ &= \frac{1}{2} k_B \Theta + k_B T \ln \left( 1 - e^{-\Theta/T} \right). \end{aligned} \quad (4.277)$$



The contribution to the heat capacity is

$$\begin{aligned}\Delta C_V &= Nk_B \left(\frac{\Theta}{T}\right)^2 \frac{e^{\Theta/T}}{(e^{\Theta/T} - 1)^2} \\ &= \begin{cases} Nk_B (\Theta/T)^2 \exp(-\Theta/T) & (T \rightarrow 0) \\ Nk_B & (T \rightarrow \infty) \end{cases}\end{aligned}\quad (4.278)$$

#### 4.10.6 Two-level systems : Schottky anomaly

Consider now a two-level system, with energies  $\varepsilon_0$  and  $\varepsilon_1$ . We define  $\Delta \equiv \varepsilon_1 - \varepsilon_0$  and assume without loss of generality that  $\Delta > 0$ . The partition function is

$$\zeta = e^{-\beta\varepsilon_0} + e^{-\beta\varepsilon_1} = e^{-\beta\varepsilon_0} (1 + e^{-\beta\Delta}). \quad (4.279)$$

The free energy is

$$f = -k_B T \ln \zeta = \varepsilon_0 - k_B T \ln (1 + e^{-\Delta/k_B T}). \quad (4.280)$$

The entropy for a given two level system is then

$$s = -\frac{\partial f}{\partial T} = k_B \ln (1 + e^{-\Delta/k_B T}) + \frac{\Delta}{T} \cdot \frac{1}{e^{\Delta/k_B T} + 1} \quad (4.281)$$

and the heat capacity is  $c = T (\partial s / \partial T)$ , i.e.

$$c(T) = \frac{\Delta^2}{k_B T^2} \cdot \frac{e^{\Delta/k_B T}}{(e^{\Delta/k_B T} + 1)^2}. \quad (4.282)$$

Thus,

$$c(T \ll \Delta) = \frac{\Delta^2}{k_B T^2} e^{-\Delta/k_B T} \quad (4.283)$$

$$c(T \gg \Delta) = \frac{\Delta^2}{4k_B T^2}. \quad (4.284)$$

We find that  $c(T)$  has a characteristic peak at  $T^* \approx 0.42 \Delta/k_B$ . The heat capacity vanishes in both the low temperature and high temperature limits. At low temperatures, the gap to the excited state is much greater than  $k_B T$ , and it is not possible to populate it and store energy. At high temperatures, both ground state and excited state are equally populated, and once again there is no way to store energy.

If we have a distribution of independent two-level systems, the heat capacity of such a system is a sum over the individual Schottky functions:

$$C(T) = \sum_i \tilde{c}(\Delta_i/k_B T) = N \int_0^\infty d\Delta P(\Delta) \tilde{c}(\Delta/T), \quad (4.285)$$

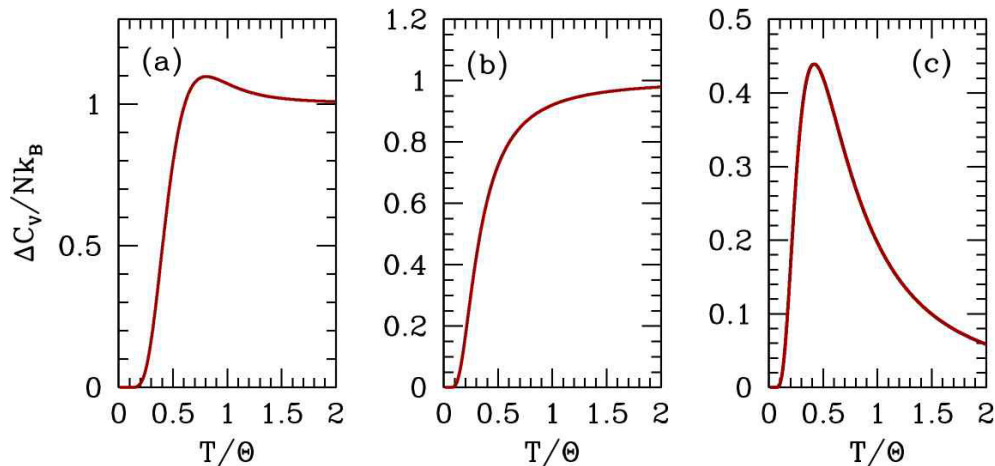


Figure 4.11: Heat capacity per molecule as a function of temperature for (a) heteronuclear diatomic gases, (b) a single vibrational mode, and (c) a single two-level system.

where  $N$  is the number of two level systems,  $\tilde{c}(x) = k_B x^2 e^x / (e^x + 1)^2$ , and where  $P(\Delta)$  is the normalized distribution function, which satisfies the normalization condition

$$\int_0^{\infty} d\Delta P(\Delta) = 1. \quad (4.286)$$

$N_S$  is the total number of two level systems. If  $P(\Delta) \propto \Delta^r$  for  $\Delta \rightarrow 0$ , then the low temperature heat capacity behaves as  $C(T) \propto T^{1+r}$ . Many amorphous or glassy systems contain such a distribution of two level systems, with  $r \approx 0$  for glasses, leading to a linear low-temperature heat capacity. The origin of these two-level systems is not always so clear but is generally believed to be associated with local atomic configurations for which there are two low-lying states which are close in energy. The paradigmatic example is the mixed crystalline solid  $(\text{KBr})_{1-x}(\text{KCN})_x$  which over the range  $0.1 \lesssim x \lesssim 0.6$  forms an ‘orientational glass’ at low temperatures. The two level systems are associated with different orientation of the cyanide (CN) dipoles.

#### 4.10.7 Electronic and nuclear excitations

For a monatomic gas, the internal coordinate partition function arises due to electronic and nuclear degrees of freedom. Let’s first consider the electronic degrees of freedom. We assume that  $k_B T$  is small compared with energy differences between successive electronic shells. The atomic ground state is then computed by filling up the hydrogenic orbitals until all the electrons are used up. If the atomic number is a ‘magic number’ ( $A = 2$  (He), 10 (Ne), 18 (Ar), 36 (Kr), 54 (Xe), etc.) then the atom has all shells filled and  $L = 0$  and  $S = 0$ . Otherwise the last shell is partially filled and one or both of  $L$  and  $S$  will be nonzero. The atomic ground state configuration  $2^{J+1}L_S$  is then determined by *Hund’s rules*:

1. The  $LS$  multiplet with the *largest*  $S$  has the lowest energy.

2. If the largest value of  $S$  is associated with several multiplets, the multiplet with the *largest*  $L$  has the lowest energy.
3. If an incomplete shell is not more than half-filled, then the lowest energy state has  $J = |L - S|$ . If the shell is more than half-filled, then  $J = L + S$ .

The last of Hund's rules distinguishes between the  $(2S+1)(2L+1)$  states which result upon fixing  $S$  and  $L$  as per rules #1 and #2. It arises due to the atomic spin-orbit coupling, whose effective Hamiltonian may be written  $\hat{H} = \Lambda \mathbf{L} \cdot \mathbf{S}$ , where  $\Lambda$  is the Russell-Saunders coupling. If the last shell is less than or equal to half-filled, then  $\Lambda > 0$  and the ground state has  $J = |L - S|$ . If the last shell is more than half-filled, the coupling is *inverted*, i.e.  $\Lambda < 0$ , and the ground state has  $J = L + S$ .<sup>8</sup>

The electronic contribution to  $\xi$  is then

$$\xi_{\text{elec}} = \sum_{J=|L-S|}^{L+S} (2J+1) e^{-\Delta\epsilon(L,S,J)/k_{\text{B}}T} \quad (4.287)$$

where

$$\Delta\epsilon(L, S, J) = \frac{1}{2}\Lambda \left[ J(J+1) - L(L+1) - S(S+1) \right]. \quad (4.288)$$

At high temperatures,  $k_{\text{B}}T$  is larger than the energy difference between the different  $J$  multiplets, and we have  $\xi_{\text{elec}} \sim (2L+1)(2S+1) e^{-\beta\epsilon_0}$ , where  $\epsilon_0$  is the ground state energy. At low temperatures, a particular value of  $J$  is selected – that determined by Hund's third rule – and we have  $\xi_{\text{elec}} \sim (2J+1) e^{-\beta\epsilon_0}$ . If, in addition, there is a nonzero nuclear spin  $I$ , then we also must include a factor  $\xi_{\text{nuc}} = (2I+1)$ , neglecting the small hyperfine splittings due to the coupling of nuclear and electronic angular momenta.

For *heteronuclear* diatomic molecules, i.e. molecules composed from two different atomic nuclei, the internal partition function simply receives a factor of  $\xi_{\text{elec}} \cdot \xi_{\text{nuc}}^{(1)} \cdot \xi_{\text{nuc}}^{(2)}$ , where the first term is a sum over molecular electronic states, and the second two terms arise from the spin degeneracies of the two nuclei. For *homonuclear* diatomic molecules, the exchange of nuclear centers is a symmetry operation, and does not represent a distinct quantum state. To correctly count the electronic states, we first assume that the total electronic spin is  $S = 0$ . This is generally a very safe assumption. Exchange symmetry now puts restrictions on the possible values of the molecular angular momentum  $L$ , depending on the total nuclear angular momentum  $I_{\text{tot}}$ . If  $I_{\text{tot}}$  is even, then the molecular angular momentum  $L$  must also be even. If the total nuclear angular momentum is odd, then  $L$  must be odd. This is so because the molecular ground state configuration is  $^1\Sigma_g^+$ .<sup>9</sup>

The total number of nuclear states for the molecule is  $(2I+1)^2$ , of which some are even under nuclear exchange, and some are odd. The number of even states, corresponding to even total nuclear angular momentum is written as  $g_g$ , where the subscript conventionally stands for the (mercifully short) German word *gerade*, meaning 'even'. The number of odd (Ger. *ungerade*) states is written  $g_u$ . Table 4.2 gives the values of  $g_{g,u}$  corresponding to half-odd-integer  $I$  and integer  $I$ .

<sup>8</sup>See e.g. §72 of Landau and Lifshitz, *Quantum Mechanics*, which, in my humble estimation, is the greatest physics book ever written.

<sup>9</sup>See Landau and Lifshitz, *Quantum Mechanics*, §86.

$2I$	$g_g$	$g_u$
odd	$I(2I + 1)$	$(I + 1)(2I + 1)$
even	$(I + 1)(2I + 1)$	$I(2I + 1)$

Table 4.2: Number of even ( $g_g$ ) and odd ( $g_u$ ) total nuclear angular momentum states for a homonuclear diatomic molecule.  $I$  is the ground state nuclear spin.

The final answer for the rotational component of the internal molecular partition function is then

$$\xi_{\text{rot}}(T) = g_g \zeta_g + g_u \zeta_u, \quad (4.289)$$

where

$$\begin{aligned} \zeta_g &= \sum_{L \text{ even}} (2L + 1) e^{-L(L+1) \Theta_{\text{rot}}/T} \\ \zeta_u &= \sum_{L \text{ odd}} (2L + 1) e^{-L(L+1) \Theta_{\text{rot}}/T}. \end{aligned} \quad (4.290)$$

For hydrogen, the molecules with the larger nuclear statistical weight are called *orthohydrogen* and those with the smaller statistical weight are called *parahydrogen*. For  $\text{H}_2$ , we have  $I = \frac{1}{2}$  hence the ortho state has  $g_u = 3$  and the para state has  $g_g = 1$ . In  $\text{D}_2$ , we have  $I = 1$  and the ortho state has  $g_g = 6$  while the para state has  $g_u = 3$ . In equilibrium, the ratio of ortho to para states is then

$$\frac{N_{\text{H}_2}^{\text{ortho}}}{N_{\text{H}_2}^{\text{para}}} = \frac{g_u \zeta_u}{g_g \zeta_g} = \frac{3 \zeta_u}{\zeta_g}, \quad \frac{N_{\text{D}_2}^{\text{ortho}}}{N_{\text{D}_2}^{\text{para}}} = \frac{g_g \zeta_g}{g_u \zeta_u} = \frac{2 \zeta_g}{\zeta_u}. \quad (4.291)$$

Incidentally, how do we derive the results in Tab. 4.10.7? The total nuclear angular momentum  $I_{\text{tot}}$  is the quantum mechanical sum of the two individual nuclear angular momenta, each of which are of magnitude  $I$ . From elementary addition of angular momenta, we have

$$I \otimes I = 0 \oplus 1 \oplus 2 \oplus \cdots \oplus 2I. \quad (4.292)$$

The right hand side of the above equation lists all the possible multiplets. Thus,  $I_{\text{tot}} \in \{0, 1, \dots, 2I\}$ . Now let us count the total number of states with *even*  $I_{\text{tot}}$ . If  $2I$  is even, which is to say if  $I$  is an integer, we have

$$g_g^{(2I=\text{even})} = \sum_{n=0}^I \left\{ 2 \cdot (2n) + 1 \right\} = (I + 1)(2I + 1), \quad (4.293)$$

because the degeneracy of each multiplet is  $2I_{\text{tot}} + 1$ . It follows that

$$g_u^{(2I=\text{even})} = (2I + 1)^2 - g_g = I(2I + 1). \quad (4.294)$$

On the other hand, if  $2I$  is odd, which is to say  $I$  is a half odd integer, then

$$g_g^{(2I=\text{odd})} = \sum_{n=0}^{I-\frac{1}{2}} \left\{ 2 \cdot (2n) + 1 \right\} = I(2I + 1). \quad (4.295)$$

It follows that

$$g_u^{(2I=\text{odd})} = (2I + 1)^2 - g_g = (I + 1)(2I + 1). \quad (4.296)$$

## 4.11 Appendix I: Additional Examples

### 4.11.1 Three state system

Consider a spin-1 particle where  $\sigma = -1, 0, +1$ . We model this with the single particle Hamiltonian

$$\hat{h} = -\mu_0 H \sigma + \Delta(1 - \sigma^2). \quad (4.297)$$

We can also interpret this as describing a spin if  $\sigma = \pm 1$  and a vacancy if  $\sigma = 0$ . The parameter  $\Delta$  then represents the vacancy formation energy. The single particle partition function is

$$\zeta = \text{Tr} e^{-\beta \hat{h}} = e^{-\beta \Delta} + 2 \cosh(\beta \mu_0 H). \quad (4.298)$$

With  $N_S$  distinguishable noninteracting spins (e.g. at different sites in a crystalline lattice), we have  $Z = \zeta^{N_S}$  and

$$F \equiv N_S f = -k_B T \ln Z = -N_S k_B T \ln \left[ e^{-\beta \Delta} + 2 \cosh(\beta \mu_0 H) \right], \quad (4.299)$$

where  $f = -k_B T \ln \zeta$  is the free energy of a single particle. Note that

$$\hat{n}_v = 1 - \sigma^2 = \frac{\partial \hat{h}}{\partial \Delta} \quad (4.300)$$

$$\hat{m} = \mu_0 \sigma = -\frac{\partial \hat{h}}{\partial H} \quad (4.301)$$

are the vacancy number and magnetization, respectively. Thus,

$$n_v = \langle \hat{n}_v \rangle = \frac{\partial f}{\partial \Delta} = \frac{e^{-\Delta/k_B T}}{e^{-\Delta/k_B T} + 2 \cosh(\mu_0 H/k_B T)} \quad (4.302)$$

and

$$m = \langle \hat{m} \rangle = -\frac{\partial f}{\partial H} = \frac{2\mu_0 \sinh(\mu_0 H/k_B T)}{e^{-\Delta/k_B T} + 2 \cosh(\mu_0 H/k_B T)}. \quad (4.303)$$

At weak fields we can compute

$$\chi_T = \left. \frac{\partial m}{\partial H} \right|_{H=0} = \frac{\mu_0^2}{k_B T} \cdot \frac{2}{2 + e^{-\Delta/k_B T}}. \quad (4.304)$$

We thus obtain a modified Curie law. At temperatures  $T \ll \Delta/k_B$ , the vacancies are frozen out and we recover the usual Curie behavior. At high temperatures, where  $T \gg \Delta/k_B$ , the low temperature result is reduced by a factor of  $\frac{2}{3}$ , which accounts for the fact that one third of the time the particle is in a nonmagnetic state with  $\sigma = 0$ .

### 4.11.2 Spins and vacancies on a surface

PROBLEM: A collection of spin- $\frac{1}{2}$  particles is confined to a surface with  $N$  sites. For each site, let  $\sigma = 0$  if there is a vacancy,  $\sigma = +1$  if there is particle present with spin up, and  $\sigma = -1$  if there is a particle present with spin down. The particles are non-interacting, and the energy for each site is given by  $\varepsilon = -W\sigma^2$ , where  $-W < 0$  is the binding energy.

- (a) Let  $Q = N_{\uparrow} + N_{\downarrow}$  be the number of spins, and  $N_0$  be the number of vacancies. The surface magnetization is  $M = N_{\uparrow} - N_{\downarrow}$ . Compute, in the microcanonical ensemble, the statistical entropy  $S(Q, M)$ .
- (b) Let  $q = Q/N$  and  $m = M/N$  be the dimensionless particle density and magnetization density, respectively. Assuming that we are in the thermodynamic limit, where  $N$ ,  $Q$ , and  $M$  all tend to infinity, but with  $q$  and  $m$  finite, Find the temperature  $T(q, m)$ . Recall Stirling's formula

$$\ln(N!) = N \ln N - N + \mathcal{O}(\ln N) .$$

- (c) Show explicitly that  $T$  can be negative for this system. What does negative  $T$  mean? What physical degrees of freedom have been left out that would avoid this strange property?

SOLUTION: There is a constraint on  $N_{\uparrow}$ ,  $N_0$ , and  $N_{\downarrow}$ :

$$N_{\uparrow} + N_0 + N_{\downarrow} = Q + N_0 = N . \quad (4.305)$$

The total energy of the system is  $E = -WQ$ .

- (a) The number of states available to the system is

$$\Omega = \frac{N!}{N_{\uparrow}! N_0! N_{\downarrow}!} . \quad (4.306)$$

Fixing  $Q$  and  $M$ , along with the above constraint, is enough to completely determine  $\{N_{\uparrow}, N_0, N_{\downarrow}\}$ :

$$N_{\uparrow} = \frac{1}{2}(Q + M) \quad , \quad N_0 = N - Q \quad , \quad N_{\downarrow} = \frac{1}{2}(Q - M) , \quad (4.307)$$

whence

$$\Omega(Q, M) = \frac{N!}{\left[\frac{1}{2}(Q + M)\right]! \left[\frac{1}{2}(Q - M)\right]! (N - Q)!} . \quad (4.308)$$

The statistical entropy is  $S = k_B \ln \Omega$ :

$$S(Q, M) = k_B \ln(N!) - k_B \ln \left[\frac{1}{2}(Q + M)\right]! - k_B \ln \left[\frac{1}{2}(Q - M)\right]! - k_B \ln [(N - Q)!] . \quad (4.309)$$

- (b) Now we invoke Stirling's rule,

$$\ln(N!) = N \ln N - N + \mathcal{O}(\ln N) , \quad (4.310)$$

to obtain

$$\begin{aligned}
\ln \Omega(Q, M) &= N \ln N - N - \frac{1}{2}(Q + M) \ln \left[ \frac{1}{2}(Q + M) \right] + \frac{1}{2}(Q + M) \\
&\quad - \frac{1}{2}(Q - M) \ln \left[ \frac{1}{2}(Q - M) \right] + \frac{1}{2}(Q - M) \\
&\quad - (N - Q) \ln(N - Q) + (N - Q) \\
&= N \ln N - \frac{1}{2}Q \ln \left[ \frac{1}{4}(Q^2 - M^2) \right] - \frac{1}{2}M \ln \left( \frac{Q + M}{Q - M} \right)
\end{aligned} \tag{4.311}$$

Combining terms,

$$\ln \Omega(Q, M) = -Nq \ln \left[ \frac{1}{2} \sqrt{q^2 - m^2} \right] - \frac{1}{2}Nm \ln \left( \frac{q + m}{q - m} \right) - N(1 - q) \ln(1 - q), \tag{4.312}$$

where  $Q = Nq$  and  $M = Nm$ . Note that the entropy  $S = k_B \ln \Omega$  is extensive. The statistical entropy per site is thus

$$s(q, m) = -k_B q \ln \left[ \frac{1}{2} \sqrt{q^2 - m^2} \right] - \frac{1}{2}k_B m \ln \left( \frac{q + m}{q - m} \right) - k_B (1 - q) \ln(1 - q). \tag{4.313}$$

The temperature is obtained from the relation

$$\begin{aligned}
\frac{1}{T} &= \left( \frac{\partial S}{\partial E} \right)_M = \frac{1}{W} \left( \frac{\partial s}{\partial q} \right)_m \\
&= \frac{1}{W} \ln(1 - q) - \frac{1}{W} \ln \left[ \frac{1}{2} \sqrt{q^2 - m^2} \right].
\end{aligned} \tag{4.314}$$

Thus,

$$T = \frac{W/k_B}{\ln[2(1 - q)/\sqrt{q^2 - m^2}]}. \tag{4.315}$$

- (c) We have  $0 \leq q \leq 1$  and  $-q \leq m \leq q$ , so  $T$  is real (thank heavens!). But it is easy to choose  $\{q, m\}$  such that  $T < 0$ . For example, when  $m = 0$  we have  $T = W/k_B \ln(2q^{-1} - 2)$  and  $T < 0$  for all  $q \in (\frac{2}{3}, 1]$ . The reason for this strange state of affairs is that the entropy  $S$  is bounded, and is not an monotonically increasing function of the energy  $E$  (or the dimensionless quantity  $Q$ ). The entropy is maximized for  $N \uparrow = N_0 = N \downarrow = \frac{1}{3}$ , which says  $m = 0$  and  $q = \frac{2}{3}$ . Increasing  $q$  beyond this point (with  $m = 0$  fixed) starts to reduce the entropy, and hence  $(\partial S / \partial E) < 0$  in this range, which immediately gives  $T < 0$ . What we've left out are kinetic degrees of freedom, such as vibrations and rotations, whose energies are unbounded, and which result in an increasing  $S(E)$  function.

### 4.11.3 Fluctuating interface

Consider an interface between two dissimilar fluids. In equilibrium, in a uniform gravitational field, the denser fluid is on the bottom. Let  $z = z(x, y)$  be the height the interface between the fluids, relative to

equilibrium. The potential energy is a sum of gravitational and surface tension terms, with

$$U_{\text{grav}} = \int d^2x \int_0^z dz' \Delta\rho g z' \quad (4.316)$$

$$U_{\text{surf}} = \int d^2x \frac{1}{2} \sigma (\nabla z)^2 . \quad (4.317)$$

We won't need the kinetic energy in our calculations, but we can include it just for completeness. It isn't so clear how to model it *a priori* so we will assume a rather general form

$$T = \int d^2x \int d^2x' \frac{1}{2} \mu(\mathbf{x}, \mathbf{x}') \frac{\partial z(\mathbf{x}, t)}{\partial t} \frac{\partial z(\mathbf{x}', t)}{\partial t} . \quad (4.318)$$

We assume that the  $(x, y)$  plane is a rectangle of dimensions  $L_x \times L_y$ . We also assume  $\mu(\mathbf{x}, \mathbf{x}') = \mu(|\mathbf{x} - \mathbf{x}'|)$ . We can then Fourier transform

$$z(\mathbf{x}) = (L_x L_y)^{-1/2} \sum_{\mathbf{k}} z_{\mathbf{k}} e^{i\mathbf{k} \cdot \mathbf{x}} , \quad (4.319)$$

where the wavevectors  $\mathbf{k}$  are quantized according to

$$\mathbf{k} = \frac{2\pi n_x}{L_x} \hat{\mathbf{x}} + \frac{2\pi n_y}{L_y} \hat{\mathbf{y}} , \quad (4.320)$$

with integer  $n_x$  and  $n_y$ , if we impose periodic boundary conditions (for calculational convenience). The Lagrangian is then

$$L = \frac{1}{2} \sum_{\mathbf{k}} \left[ \mu_{\mathbf{k}} |\dot{z}_{\mathbf{k}}|^2 - (g \Delta\rho + \sigma \mathbf{k}^2) |z_{\mathbf{k}}|^2 \right] , \quad (4.321)$$

where

$$\mu_{\mathbf{k}} = \int d^2x \mu(|\mathbf{x}|) e^{-i\mathbf{k} \cdot \mathbf{x}} . \quad (4.322)$$

Since  $z(\mathbf{x}, t)$  is real, we have the relation  $z_{-\mathbf{k}} = z_{\mathbf{k}}^*$ , therefore the Fourier coefficients at  $\mathbf{k}$  and  $-\mathbf{k}$  are not independent. The canonical momenta are given by

$$p_{\mathbf{k}} = \frac{\partial L}{\partial \dot{z}_{\mathbf{k}}^*} = \mu_{\mathbf{k}} \dot{z}_{\mathbf{k}} \quad , \quad p_{\mathbf{k}}^* = \frac{\partial L}{\partial \dot{z}_{\mathbf{k}}} = \mu_{\mathbf{k}} \dot{z}_{\mathbf{k}}^* \quad (4.323)$$

The Hamiltonian is then

$$\hat{H} = \sum'_{\mathbf{k}} \left[ p_{\mathbf{k}} z_{\mathbf{k}}^* + p_{\mathbf{k}}^* z_{\mathbf{k}} \right] - L \quad (4.324)$$

$$= \sum'_{\mathbf{k}} \left[ \frac{|p_{\mathbf{k}}|^2}{\mu_{\mathbf{k}}} + (g \Delta\rho + \sigma \mathbf{k}^2) |z_{\mathbf{k}}|^2 \right] , \quad (4.325)$$

where the prime on the  $\mathbf{k}$  sum indicates that only one of the pair  $\{\mathbf{k}, -\mathbf{k}\}$  is to be included, for each  $\mathbf{k}$ .



We may now compute the ordinary canonical partition function:

$$\begin{aligned} Z &= \prod'_k \int \frac{d^2 p_{\mathbf{k}} d^2 z_{\mathbf{k}}}{(2\pi\hbar)^2} e^{-|p_{\mathbf{k}}|^2/\mu_{\mathbf{k}}k_{\text{B}}T} e^{-(g\Delta\rho+\sigma k^2)|z_{\mathbf{k}}|^2/k_{\text{B}}T} \\ &= \prod'_k \left( \frac{k_{\text{B}}T}{2\hbar} \right)^2 \left( \frac{\mu_{\mathbf{k}}}{g\Delta\rho + \sigma k^2} \right). \end{aligned} \quad (4.326)$$

Thus,

$$F = -k_{\text{B}}T \sum_{\mathbf{k}} \ln \left( \frac{k_{\text{B}}T}{2\hbar\Omega_{\mathbf{k}}} \right), \quad (4.327)$$

where<sup>10</sup>

$$\Omega_{\mathbf{k}} = \left( \frac{g\Delta\rho + \sigma k^2}{\mu_{\mathbf{k}}} \right)^{1/2}. \quad (4.328)$$

is the normal mode frequency for surface oscillations at wavevector  $\mathbf{k}$ . For deep water waves, it is appropriate to take  $\mu_{\mathbf{k}} = \Delta\rho/|\mathbf{k}|$ , where  $\Delta\rho = \rho_{\text{L}} - \rho_{\text{G}} \approx \rho_{\text{L}}$  is the difference between the densities of water and air.

It is now easy to compute the thermal average

$$\begin{aligned} \langle |z_{\mathbf{k}}|^2 \rangle &= \int d^2 z_{\mathbf{k}} |z_{\mathbf{k}}|^2 e^{-(g\Delta\rho+\sigma k^2)|z_{\mathbf{k}}|^2/k_{\text{B}}T} / \int d^2 z_{\mathbf{k}} e^{-(g\Delta\rho+\sigma k^2)|z_{\mathbf{k}}|^2/k_{\text{B}}T} \\ &= \frac{k_{\text{B}}T}{g\Delta\rho + \sigma k^2}. \end{aligned} \quad (4.329)$$

Note that this result does not depend on  $\mu_{\mathbf{k}}$ , *i.e.* on our choice of kinetic energy. One defines the *correlation function*

$$\begin{aligned} C(\mathbf{x}) &\equiv \langle z(\mathbf{x})z(0) \rangle = \frac{1}{L_x L_y} \sum_{\mathbf{k}} \langle |z_{\mathbf{k}}|^2 \rangle e^{i\mathbf{k}\cdot\mathbf{x}} = \int \frac{d^2 k}{(2\pi)^2} \left( \frac{k_{\text{B}}T}{g\Delta\rho + \sigma k^2} \right) e^{i\mathbf{k}\cdot\mathbf{x}} \\ &= \frac{k_{\text{B}}T}{4\pi\sigma} \int_0^\infty dq \frac{e^{ik|\mathbf{x}|}}{\sqrt{q^2 + \xi^2}} = \frac{k_{\text{B}}T}{4\pi\sigma} K_0(|\mathbf{x}|/\xi), \end{aligned} \quad (4.330)$$

where  $\xi = \sqrt{g\Delta\rho/\sigma}$  is the correlation length, and where  $K_0(z)$  is the Bessel function of imaginary argument. The asymptotic behavior of  $K_0(z)$  for small  $z$  is  $K_0(z) \sim \ln(2/z)$ , whereas for large  $z$  one has  $K_0(z) \sim (\pi/2z)^{1/2} e^{-z}$ . We see that on large length scales the correlations decay exponentially, but on small length scales they diverge. This divergence is due to the improper energetics we have assigned to short wavelength fluctuations of the interface. Roughly, it can be cured by imposing a cutoff on the integral, or by insisting that the shortest distance scale is a molecular diameter.

<sup>10</sup>Note that there is no prime on the  $\mathbf{k}$  sum for  $F$ , as we have divided the logarithm of  $Z$  by two and replaced the half sum by the whole sum.

#### 4.11.4 Dissociation of molecular hydrogen

Consider the reaction



In equilibrium, we have

$$\mu_{\text{H}} = \mu_{\text{p}} + \mu_{\text{e}} . \quad (4.332)$$

What is the relationship between the temperature  $T$  and the fraction  $x$  of hydrogen which is dissociated?

Let us assume a fraction  $x$  of the hydrogen is dissociated. Then the densities of H, p, and e are then

$$n_{\text{H}} = (1 - x)n \quad , \quad n_{\text{p}} = xn \quad , \quad n_{\text{e}} = xn . \quad (4.333)$$

The single particle partition function for each species is

$$\zeta = \frac{g^N}{N!} \left( \frac{V}{\lambda_T^3} \right)^N e^{-N\varepsilon_{\text{int}}/k_{\text{B}}T} , \quad (4.334)$$

where  $g$  is the degeneracy and  $\varepsilon_{\text{int}}$  the internal energy for a given species. We have  $\varepsilon_{\text{int}} = 0$  for p and e, and  $\varepsilon_{\text{int}} = -\Delta$  for H, where  $\Delta = e^2/2a_{\text{B}} = 13.6 \text{ eV}$ , the binding energy of hydrogen. Neglecting hyperfine splittings<sup>11</sup>, we have  $g_{\text{H}} = 4$ , while  $g_{\text{e}} = g_{\text{p}} = 2$  because each has spin  $S = \frac{1}{2}$ . Thus, the associated grand potentials are

$$\Omega_{\text{H}} = -g_{\text{H}} V k_{\text{B}} T \lambda_{T,\text{H}}^{-3} e^{(\mu_{\text{H}} + \Delta)/k_{\text{B}}T} \quad (4.335)$$

$$\Omega_{\text{p}} = -g_{\text{p}} V k_{\text{B}} T \lambda_{T,\text{p}}^{-3} e^{\mu_{\text{p}}/k_{\text{B}}T} \quad (4.336)$$

$$\Omega_{\text{e}} = -g_{\text{e}} V k_{\text{B}} T \lambda_{T,\text{e}}^{-3} e^{\mu_{\text{e}}/k_{\text{B}}T} , \quad (4.337)$$

where

$$\lambda_{T,a} = \sqrt{\frac{2\pi\hbar^2}{m_a k_{\text{B}}T}} \quad (4.338)$$

for species  $a$ . The corresponding number densities are

$$n = \frac{1}{V} \left( \frac{\partial \Omega}{\partial \mu} \right)_{T,V} = g \lambda_T^{-3} e^{(\mu - \varepsilon_{\text{int}})/k_{\text{B}}T} , \quad (4.339)$$

and the fugacity  $z = e^{\mu/k_{\text{B}}T}$  of a given species is given by

$$z = g^{-1} n \lambda_T^3 e^{\varepsilon_{\text{int}}/k_{\text{B}}T} . \quad (4.340)$$

We now invoke  $\mu_{\text{H}} = \mu_{\text{p}} + \mu_{\text{e}}$ , which says  $z_{\text{H}} = z_{\text{p}} z_{\text{e}}$ , or

$$g_{\text{H}}^{-1} n_{\text{H}} \lambda_{T,\text{H}}^3 e^{-\Delta/k_{\text{B}}T} = (g_{\text{p}}^{-1} n_{\text{p}} \lambda_{T,\text{p}}^3) (g_{\text{e}}^{-1} n_{\text{e}} \lambda_{T,\text{e}}^3) , \quad (4.341)$$

<sup>11</sup>The hyperfine splitting in hydrogen is on the order of  $(m_{\text{e}}/m_{\text{p}}) \alpha^4 m_{\text{e}} c^2 \sim 10^{-6} \text{ eV}$ , which is on the order of 0.01 K. Here  $\alpha = e^2/\hbar c$  is the fine structure constant.

which yields

$$\left(\frac{x^2}{1-x}\right) n \tilde{\lambda}_T^3 = e^{-\Delta/k_B T}, \quad (4.342)$$

where  $\tilde{\lambda}_T = \sqrt{2\pi\hbar^2/m^*k_B T}$ , with  $m^* = m_p m_e/m_H \approx m_e$ . Note that

$$\tilde{\lambda}_T = a_B \sqrt{\frac{4\pi m_H}{m_p}} \sqrt{\frac{\Delta}{k_B T}}, \quad (4.343)$$

where  $a_B = 0.529 \text{ \AA}$  is the Bohr radius. Thus, we have

$$\left(\frac{x^2}{1-x}\right) \cdot (4\pi)^{3/2} \nu = \left(\frac{T}{T_0}\right)^{3/2} e^{-T_0/T}, \quad (4.344)$$

where  $T_0 = \Delta/k_B = 1.578 \times 10^5 \text{ K}$  and  $\nu = n a_B^3$ . Consider for example a temperature  $T = 3000 \text{ K}$ , for which  $T_0/T = 52.6$ , and assume that  $x = \frac{1}{2}$ . We then find  $\nu = 1.69 \times 10^{-27}$ , corresponding to a density of  $n = 1.14 \times 10^{-2} \text{ cm}^{-3}$ . At this temperature, the fraction of hydrogen molecules in their first excited (2s) state is  $x' \sim e^{-T_0/2T} = 3.8 \times 10^{-12}$ . This is quite striking: half the hydrogen atoms are completely dissociated, which requires an energy of  $\Delta$ , yet the number in their first excited state, requiring energy  $\frac{1}{2}\Delta$ , is twelve orders of magnitude smaller. The student should reflect on why this can be the case.