

(a) The total energy of the system is

$$E = \sum_{i=1}^N \epsilon_i n_i = \sum_{i=1}^N \epsilon_i \langle n_i \rangle$$
 In the grand canonical ensemble, the average energy is

$$\langle E \rangle = \frac{1}{\mathcal{Z}} \sum_{\{n_i\}} E e^{-\beta E - \beta \sum_{i=1}^N \mu_i n_i}$$
 where $\mathcal{Z} = \sum_{\{n_i\}} e^{-\beta E - \beta \sum_{i=1}^N \mu_i n_i}$ is the grand partition function.
 For a single site i , the grand partition function is

$$\mathcal{Z}_i = \sum_{n_i=0}^{\infty} e^{-\beta \epsilon_i n_i - \beta \mu_i n_i} = \sum_{n_i=0}^{\infty} e^{-\beta (\epsilon_i + \mu_i) n_i} = \frac{1}{1 - e^{-\beta (\epsilon_i + \mu_i)}}$$
 The average number of particles on site i is

$$\langle n_i \rangle = \frac{1}{\mathcal{Z}_i} \sum_{n_i=0}^{\infty} n_i e^{-\beta (\epsilon_i + \mu_i) n_i} = \frac{e^{-\beta (\epsilon_i + \mu_i)}}{1 - e^{-\beta (\epsilon_i + \mu_i)}}$$
 The average energy is

$$\langle E \rangle = \sum_{i=1}^N \epsilon_i \langle n_i \rangle = \sum_{i=1}^N \epsilon_i \frac{e^{-\beta (\epsilon_i + \mu_i)}}{1 - e^{-\beta (\epsilon_i + \mu_i)}}$$
 (b) The total entropy of the system is

$$S = -k_B \sum_{i=1}^N \sum_{n_i=0}^{\infty} p_{i,n_i} \ln p_{i,n_i}$$
 where $p_{i,n_i} = \frac{1}{\mathcal{Z}_i} e^{-\beta (\epsilon_i + \mu_i) n_i}$ is the probability of finding n_i particles on site i .
 For a single site i , the entropy is

$$S_i = -k_B \sum_{n_i=0}^{\infty} p_{i,n_i} \ln p_{i,n_i} = -k_B \left[\sum_{n_i=0}^{\infty} p_{i,n_i} \ln \left(\frac{1}{\mathcal{Z}_i} e^{-\beta (\epsilon_i + \mu_i) n_i} \right) \right]$$

$$= -k_B \left[\sum_{n_i=0}^{\infty} p_{i,n_i} \ln \mathcal{Z}_i - \sum_{n_i=0}^{\infty} p_{i,n_i} \ln e^{-\beta (\epsilon_i + \mu_i) n_i} \right]$$

$$= -k_B \left[\ln \mathcal{Z}_i - \beta (\epsilon_i + \mu_i) \sum_{n_i=0}^{\infty} p_{i,n_i} n_i \right]$$

$$= -k_B \left[\ln \frac{1}{1 - e^{-\beta (\epsilon_i + \mu_i)}} - \beta (\epsilon_i + \mu_i) \frac{e^{-\beta (\epsilon_i + \mu_i)}}{1 - e^{-\beta (\epsilon_i + \mu_i)}} \right]$$
 The total entropy is

$$S = \sum_{i=1}^N S_i = \sum_{i=1}^N -k_B \left[\ln \frac{1}{1 - e^{-\beta (\epsilon_i + \mu_i)}} - \beta (\epsilon_i + \mu_i) \frac{e^{-\beta (\epsilon_i + \mu_i)}}{1 - e^{-\beta (\epsilon_i + \mu_i)}} \right]$$

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