FYS–7206 Biological Physics / FYS–7200 Biologinen Fysiikka

Exam 10.12.2014

A pocket calculator and one A4-paper (two-sided) of hand-written notes are allowed in the exam. The notes have to be returned together with the exam paper.

You may give your answers either in Finnish or English, as you prefer.

Course versions:

If you wish to complete the 3-cr version, choose Assignments 1-6
If you wish to complete the 5-cr version, choose Assignments 1-4 and 7-8

These might be useful:

Taylor expansion

\[ \sum_{n=0}^{\infty} \frac{f^{(n)}(a)}{n!} (x - a)^n \]

Boltzmann constant \(1.380662 \cdot 10^{-23} \text{ J/K}\)

1 amu = \(1.66 \times 10^{-27} \text{ kg (atomic mass unit)}\)

Viscosity of water \(\eta = 10^{-5} \text{ kg / ms}\)

\[ \int_{-\infty}^{\infty} e^{-x^2} \, dx = \sqrt{\pi} \]
Assignments 1-4 are common to both versions of the course

Assignment 1.  (5 p)

Explain the following concepts and terms.
  a) Osmosis
  b) Hydrophobic interaction
  c) Chemical potential
  d) Reynolds number
  e) Nernst potential

Assignment 2.  (3 p)

a) Describe what happens to an organism when it reaches the state of maximum entropy. (1 p)
b) Cells contain a variety of macromolecules. Attractive forces, such as depletion force and van der Waals force, are constantly trying to stick the macromolecules together. Use the Figure X to explain one mechanism that prevents the sticking of all macromolecules together into a useless clump. (2 p)

Assignment 3.  (4 p)

Analyze the concentration profiles in Figure 1 using Fick’s laws, that is, in each case, describe:
  - direction of flux, how the flux varies with x, how the flux changes in time
  - how the concentration profile changes in time

![Figure 1: Schematic concentration profiles](image)

Assignment 4.  (3 p)

Helix-coil transition

a) How can transitions between macromolecular states be sharp, even if the conformations are governed by weak interactions (like H-bonds) and constantly bombarded by thermal fluctuations? (1 p)
b) What is actually meant by 'sharp' in this case? (1 p)
c) Assume that: The alpha helix form has greater energy per monomer than the random-coil form, or $\Delta E_{\text{bond}} > 0$, and forming an H-bond decreases the molecule’s conformational entropy, or $\Delta S_{\text{conf}} < 0$. Now, if alpha helix formation is energetically unfavourable, and if it also reduces the conformational entropy of the chain, then why would helices ever form at any temperature? (1 p)
Assignments 5-6: choose these if you wish to complete the 3-cr version

Assignment 5. (7 p)
Consider a normal carton of homogenized milk. To simplify things, think about the milk as a colloidal dispersion of tiny fat droplets in water. The point in the homogenization of milk is to reduce the size of the fat droplets so as to prevent creaming (that is, gathering of the fat droplets to the surface of milk).

a) Using the concept of free energy, explain (qualitatively) how you would expect the droplets to be distributed in the carton (in equilibrium, however assume they stay as droplets and do not fuse). (1 p)

b) We would surely like the fats droplets to be almost uniformly distributed in our milk carton, let’s say we want the concentration on the bottom of the container to be 99% of that on the surface. What should the size of the fat droplets have to be to achieve this?

What does the situation look like (in equilibrium) if you consider fat droplets of the actual size (around 0.1-1 μm) in homogenized milk? Is the concentration still close to uniform throughout the milk carton? (3 p)

c) Clarify the situation further by calculating how long it takes for a fat droplet (size 1 μm) to travel from the bottom of the carton to the top.

Discuss the practical relevance of these results. (3 p)

Assignment 6. (8 p)

a) In Figure 2 you see a schematic free energy landscape for an imaginary enzymatic reaction. S and P refer to substrate and product, respectively. Describe briefly what is happening at the different stages of the reaction, marked with the arrows 1-5. (3 p)

b) Discuss what the height (order of magnitude) of the free energy barrier (a) in the figure should be for a typical enzyme in the cell? (1 p)

c) Assume now that the reaction involves one substrate and two products:

\[ S \rightleftharpoons P_1 + P_2 \]

with concentrations \( c_S = 10\text{mM}, c_{P_1} = 10\text{mM}, \text{and} \ c_{P_2} = 1\text{mM}. \) We take the standard concentration to be \( c_S = 1\text{M}. \) The standard free energy change for this reaction is \( \Delta G^\circ = -12.4 k_B T. \) Calculate the free energy difference (b) in the figure. (3 p)

d) Define/explain what is a reaction coordinate. (1 p)

![Figure 2: A schematic free energy landscape for a cyclic enzymatic reaction.](image)
Assignments 7-8: choose these if you wish to complete the 5-cr version

Assignment 7. (7 p)
Consider a normal carton of homogenized milk. To simplify things, think about the milk as a colloidal dispersion of tiny fat droplets in water. The point in the homogenization of milk is to reduce the size of the fat droplets so as to prevent creaming (that is, gathering of the fat droplets to the surface of milk).

a) First consider the velocity at which an average fat droplet drifts due to the field. Then find the flux of particles in the suspension and finally show that in equilibrium the concentration profile $c(x)$ of the particles is given by the Boltzmann distribution (5 p).

b) In (a) you found a concentration profile $c(x)$ of the form $c(x) = constant \cdot \exp()$. Assume now that the total number of droplets is $N$. Find an expression for the constant as a function of $N$. (2 p)

Assignment 8. (8 p)

a) In Figure 2 (see previous page) you see a schematic free energy landscape for an imaginary enzymatic reaction. $S$ and $P$ refer to substrate and product, respectively. Describe briefly what is happening at the different stages of the reaction, marked with the arrows 1-5. (2 p)

b) Assume now that the reaction involves one substrate and two products:

$$S \leftrightarrow P_1 + P_2$$

with concentrations $c_S = 10\text{mM}$, $c_{P_1} = 10\text{mM}$, and $c_{P_2} = 1\text{mM}$. We take the standard concentration to be $c_S = 1\text{M}$. The standard free energy change for this reaction is $\Delta G^\circ = -12.4k_BT$. Calculate the free energy difference (b) in the figure. (2 p)

c) Assume the reaction that our enzyme here catalyzes involves breaking a covalent bond (bond energy around hundreds of $k_BT$). What if there were no enzyme present, how much longer would it take for the reaction to proceed, compared to the catalyzed case? Calculate a rough estimate and justify your answer. (2 p)

d) Now consider an enzymatic reaction summarized by the following reaction diagram:

$$E + S \xrightarrow{k_{_{ES}}} ES \xrightarrow{k_{_{E^+}}} E + P$$

Let $P_E$ and $P_{ES}$ denote the probabilities to be in states $E$ and $ES$, respectively. Start by analyzing how $P_E$ changes in time, then find an expression for $P_{ES}$ in quasi-steady state. Use this expression to find the rate at which a single enzyme creates product. (2 p)