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Sample Question Solutions for the Chemistry of Life Topic Test

1. Enzymes play a crucial role in biology by serving as biological catalysts, increasing the rates of biochemical reactions by decreasing their activation energies. A commonly-used model for these enzyme-catalyzed reactions is the Michaelis-Menten model:

$$E + S \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} ES \xrightarrow{k_2} P$$

Where E is the enzyme, S is the substrate, ES is the enzyme-substrate complex, and P is the product.

a. Write 3 rate equations, one for the formation of ES from E and S, one for the reverse of that reaction, and one for the formation of P from ES, using the 3 different rate constant given above for this reaction model.

$$\text{Formation rate of ES} = k_1[E][S]$$

$$\text{Decomposition rate of ES} = k_{-1}[ES]$$

$$\text{Formation rate of P} = k_2[ES]$$

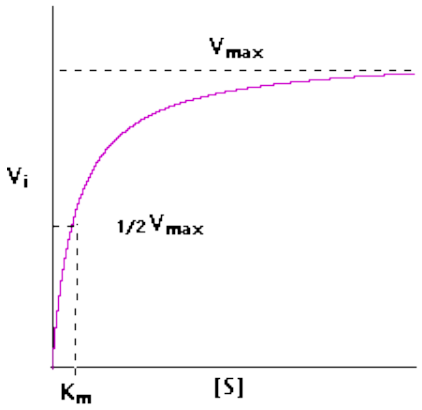
b. Using these three rate equations, one can derive the Michaelis-Menten equation describing reaction rate, V as a function of substrate concentration, [S]:

$$V([S]) = \frac{V_{max} * [S]}{K_m + [S]}$$

Where V_{max} and K_m are constants. Draw a graph of V as a function of [S]. As [S] approaches infinity, does the rate also approach infinity? Provide a brief relation in terms of kinetics for this relationship.

Rate does not go to infinity

The kinetics begin approximating first-order kinetics, but change to zero order as [S] increases.



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c. An important enzyme-catalyzed reaction is the conversion of glucose into glucose-6-phosphate. Suppose Abhi wants to synthesize glucose-6-phosphate from glucose *in vitro*. However, when he mixes the reagents in a test tube, he notices that no glucose-6-phosphate forms. He decides to add some hexokinase enzyme to speed the reaction up. Supposing that at these conditions, the reaction is endergonic ($\Delta G > 0$), will Abhi's plan work? Briefly explain your answer, and suggest an alternative strategy that involves the enzyme phosphoglucose isomerase, which converts glucose-6-phosphate into fructose-6-phosphate, a different molecule.

_Because enzymes do not change the thermodynamics of the reaction (only kinetics), the hexokinase enzyme will not be able to make the reaction exergonic on its own. Endergonic reactions do not occur spontaneously. If the phosphoglucose isomerase enzyme is used, the concentration of glucose-6-phosphate will be decreased, which will shift the reaction quotient and push the reaction closer to being exergonic. _____

d. In living cells, the synthesis of glucose-6-phosphate is just one step in a long pathway of chemical reactions whose end product is adenosine triphosphate (ATP), which is used ubiquitously as a source of energy to fuel the processes of life. As a fuel source, ATP is constantly being consumed. Explain how this allows endergonic reactions like the synthesis of glucose-6-phosphate to occur.

_ The consumption of ATP means that the use of ATP must be an exergonic and spontaneous reaction. When a spontaneous process is coupled to endergonic processes, the overall change in free energy of the reactions is negative, so those endergonic processes are pulled along by the consumption of ATP.

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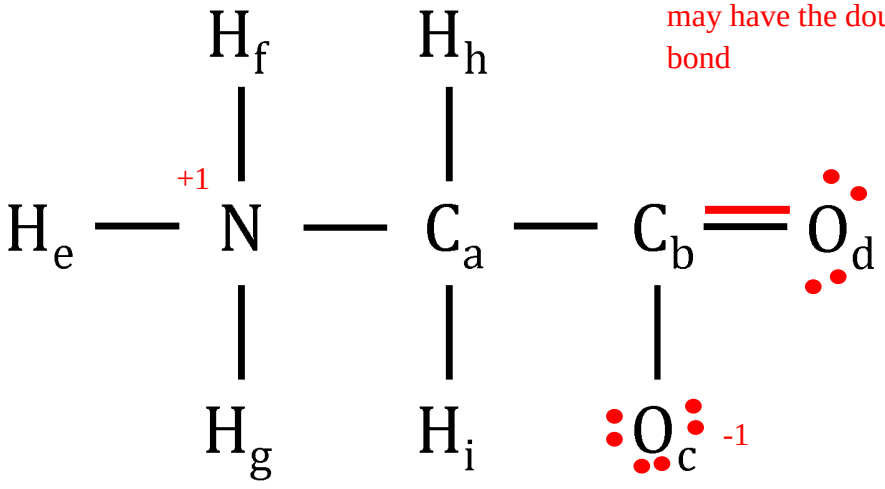
2. In biology there are 4 essential macromolecules that allow for the existence of organisms and each are essential in their own way. One class of these macromolecules is proteins. Proteins are more involved in the human body than many think. They act as enzymes, antibodies, hemoglobin, cell membrane receptors and many more vital structures. These large and complex proteins are composed of many amino acids. Unique combinations of amino acids give proteins unique properties and functions.

a. One specific amino acid is glycine, which is the smallest possible amino acid. Use the subscript letters on atoms help differentiate between identical atoms being questioned.

i. The skeleton structure of glycine is given below. Complete a single preferred Lewis structure of glycine by adding bonds and electrons wherever necessary. In addition, label all **non-zero** formal charges directly on each atom. The molecule should be **neutral** overall.

Note, either O_d or O_c may have the double bond



ii. What are the bond orders of **C_b-O_c** and **C_b-O_d**? Show necessary calculations.

Has two resonance structures. Both C-O bonds are single (bond order = 1) in one and double (bond order = 2) in the other, so overall bond order is (1+2)/2 = 1.5

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iii. How do the bond strengths and bond lengths of the **C_b-O_c** and **C_b-O_d** bonds compare to the strength and length of the double bond present in diatomic oxygen? Explain in 2-4 sentences on the lines provided below.

__Diatomic oxygen has a bond order of 2, so both of the C-O bonds above are weaker and as a result, shorter._____

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iv. What is the bond angle between **H_e** and **H_f** and what is the hybridization of the nitrogen in glycine?

Hybridization is sp^3, angle is 109.5 degrees

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b. A protein/enzyme located in the human body is catalase, which is known to act as a catalyst in order to break down hydrogen peroxide. In large quantities, hydrogen peroxide is lethal to humans, but with the addition of the catalase protein, it can decompose into harmless water and oxygen.

$$2H_2O_2 \rightarrow H_2O + O_2$$

i. Given the decomposition reaction for hydrogen peroxide above, explain whether the hydrogen peroxide is the reducing or oxidizing agent, using half-reactions as evidence.

Oxidation: $H_2O_2 \rightarrow O_2 + 2e^- + 2H^+$

Reduction: $H_2O_2 + 2e^- + 2H^+ \rightarrow 2H_2O$

It's both!

ii. If this reaction results in the release of Gibbs free energy, why is the addition of catalase necessary in order to prevent the accumulation of hydrogen peroxide in the human body?

Gibbs free energy is a thermodynamic principle and tells us nothing about the rate with which the reaction occurs. Without catalase to catalyze the reaction, decomposition would be too slow and accumulation would occur.

c. A cell membrane is present in, and essential for animal cells. This structure has both hydrophobic and hydrophilic properties. One fundamental aspect of animal cells is the movement of molecules and ions across both sides of the membrane. However, not all molecules/ions are able to move across this membrane and require the use of proteins to either facilitate or "pump" them into and/or out of a cell. A specific transport mechanism in certain animal cells is the sodium-potassium pump used to transport three sodium ions out of the cell as well as two potassium ions into the cell across the membrane.

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i. Since this pump requires the input of energy to allow the successful transport of the sodium and potassium, what does this imply about the relative concentrations of sodium and potassium inside and outside the cell? Remember that movement of a solute down its concentration gradient releases energy.

$$[Na^+]_{out} > [Na^+]_{in}$$
$$[K^+]_{out} < [K^+]_{in}$$

Since the transport requires energy, movement of both ions must be against their concentration gradient.

ii. Why does an electrochemical gradient forms as a result of the sodium-potassium pump? Remember that the ions cannot cross the membrane on their own, because of the hydrophobic parts of the membrane.

2 answers are acceptable here:

1) Different numbers of charges are moved across the membrane by the pump, leading to a difference in charges across the membrane (since ions can't diffuse across the membrane), and this is the cause of the gradient
2) If a student has some biology background, they will know that potassium can "leak" across the membrane, and this makes the charge difference more dramatic.

iii. In red blood cells, water is in equilibrium with the environment. Water is easily able to enter and exit these cells through aquaporin proteins solely by diffusion. If these red blood cells were introduced to a hypotonic solution (a solution with a lower concentration of ions than inside of the cell), describe the net movement of water into or out of the cell.

Since concentration of ions outside cell is lower than that inside the cell, the concentration of water outside the cell is higher than that inside the cell. Therefore, there will be a net movement of water into the cell.

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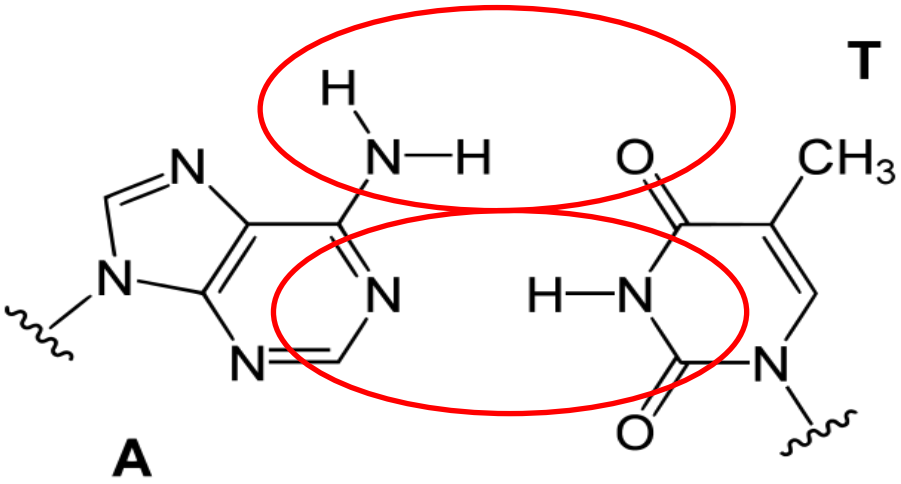
3. DNA (deoxyribonucleic acid), the molecule that stores all the genetic information of life, is a polymer made up of monomers called "bases." These DNA bases are bonded covalently into long strands, where the covalent bonds run down the length of the strand. The full DNA molecule consists of two intertwined strands, which are connected to each other with strong intermolecular interactions.

a. What is the strong intermolecular force that holds these molecules together?

Hydrogen-bonding (Note: there is some controversy as to whether hydrogen-bonding actually stabilizes a paired DNA molecule, which is regularly taught in high school chemistry and biology courses. The evidence indicates that nonpolar interactions between bases, known as base-stacking is the predominant factor, while hydrogen bonding provides little to no stabilizing effect and in some cases actually make formation of the DNA duplex unfavorable. See, for example, Yakovchuk et al. 2006. However, given that the hydrogen bonding theory is widely taught, we will accept both this and base-stacking as correct answers).

b. On the diagram below, circle all pairs of groups that have the potential to form those intermolecular interactions from part a(i) between molecules.



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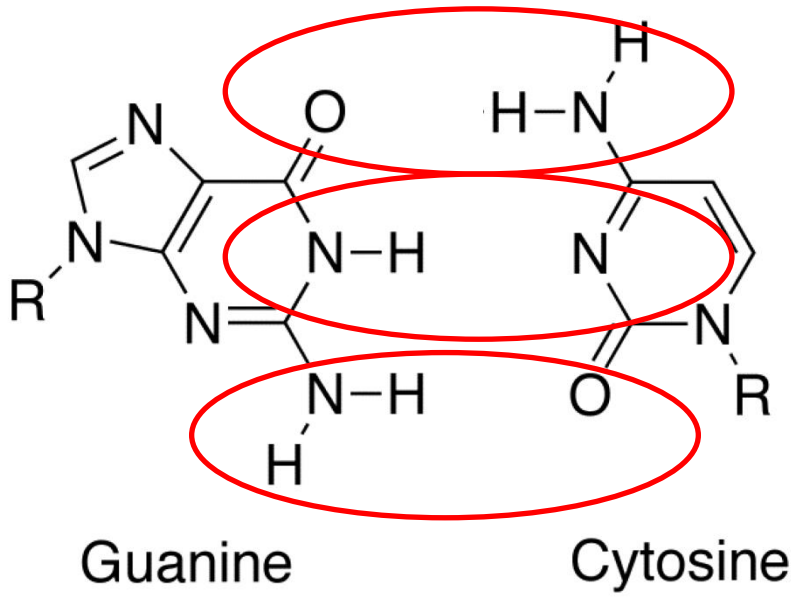
c. Shown below are the cytosine (C) and guanine (G) base pairs. Again, circle pairs of groups that are able to form the strong intermolecular interactions between the bases.



d. Assume that each of the intermolecular attractions identified in parts (a) and (b) are equally strong. The enthalpy of each interaction is 10 kJ/mol. A small amount of DNA is synthesized, with the composition being shown below. Each strand consists of covalently bonded DNA bases and base pairing occurs between A and T bases, and G and C bases on different strands.

Strand 1: A-T-G-C-G-A-T-A-G-C-T-A-T-G-C-T-A-A-T-T-G
Strand 2: T-A-C-G-C-T-A-T-C-G-A-T-A-C-G-A-T-T-A-A-C

How much energy, in joules, would be needed to separate these two strands?
21 interaction * 10000J/mol /(6.022 * 10^23) = 3.5 * 10^-19J

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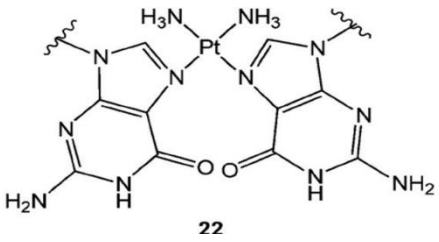
e. In order to replicate, cells must copy all of their DNA. The first step of this process is separating the two strands of each DNA molecule. This is done by a type of protein called a helicase.

i. Some helicase enzymes use the energy of a reaction called "ATP hydrolysis" to separate the strands. If the equilibrium constant for the hydrolysis of ATP at 37 °C is 19.4, calculate the change in free energy in kJ/mol of this hydrolysis.

$$\Delta G = RTln(K) = 8.314\frac{J}{mol * K} * 310K * \ln(19.4) = 7643J$$

ii. If cells cannot separate the strands of DNA, the result can be cell death. A drug called cisplatin is able to form covalent bonds between DNA bases on different strands, as shown below. The covalent bonds between the platinum of the drug and the nitrogen of the DNA base have estimated bond dissociation energies of 85 kJ/mol. Using the results of part d (i) and remembering that a normal intermolecular interaction between DNA strands is on the order of 10 kJ/mol, explain why cisplatin is able to kill cells.



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https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2505341/

Cisplatin prevents the strands from being separated. The bonds between the DNA and cisplatin are much stronger (85 vs 10 kJ/mol) and thus take much more energy to break. The energy provided by ATP hydrolysis (7 kJ) is low compared to the bond energy of cis-platin linked DNA, so traditional reactions used by the cell to separate DNA become ineffective. As a result, DNA separation does not occur, leading to cell death.