Final Examination

CHMI 2227E – Biochemistry I

Prof: Eric R. Gauthier, Ph.D.

YOUR NAME: ______________________________

YOUR STUDENT NUMBER: _____________

GUIDELINES:

1) Duration: 3 hours
2) 90 questions, on 19 pages.
3) Total of 220 marks. Counts for 45% of the final mark.
4) Questions 1-89 (multiple choice/true or false): use the answer sheet provided to you.
5) Question 90: write your answer directly on this questionnaire, limiting yourself to the allotted space.
6) The use of the University-approved calculator is authorized.
7) The use of books, notes is forbidden.
8) Have a good summer!
MULTIPLE CHOICE – SECTION A.
Choose the one alternative that best completes the statement or answers the question. 2 marks per question.

1) The last common ancestor of modern organisms must have used
   A) either D or L amino acids.   B) L amino acids.
   C) D amino acids.   D) both D and L amino acids.

2) Amino acids with non-ionizable side chains are zwitterions when they are ______.
   A) in alkaline solutions only
   B) in any solution
   C) at physiological pH, pH = 7.4
   D) in acidic solutions only
   E) All of the above

3) Tyrosine and tryptophan are less hydrophobic than phenylalanine because
   A) phenylalanine has no polar group in the side chain.
   B) phenylalanine is a phenol.
   C) tyrosine and tryptophan have smaller R groups.
   D) phenylalanine has an indole group.
   E) All of the above

4) Proteins can be modified by adding ______ to protein residues.
   A) sugars and phosphate groups
   B) polypeptides
   C) cystine
   D) A and B
   E) All of the above

5) Which amino acid is ideal for the transfer of protons within the catalytic site of enzymes due to
   the presence of significant amounts of both the protonated and deprotonated forms of its side
   chain at biological pH (i.e. pH ~ 7.4)?
   A) Lysine
   B) Cysteine
   C) Histidine
   D) Asparagine
   E) Tyrosine

6) The pK_a's of arginine's α-carboxyl group, α-amino group and side chain are 1.8, 9.0 and 12.5,
   respectively. Calculate the isoelectric point.
   A) 7.2   B) 10.8   C) 5.4   D) 7.8

7) The pK_a of a certain weak acid is 4.0. Calculate the ratio of proton acceptor to proton donor at
   pH 7.0.
   A) 3:1   D) 1000:1
   B) 20:1   E) The ratio cannot be calculated without knowing the structure of the acid.
   C) 1:1
8) The isoelectric point of alanine is pH = 6.15. It is mixed with proline (pKαCOOH = 2.0; pKαNH₂ = 10.6), and the mixture is spotted on a piece of filter paper and placed in an electric field at pH 6.15. Which statement is true?
   A) Both amino acids will move from the spot and be separated.
   B) Neither amino acid will move in the electric field.
   C) The two amino acids will be separated.
   D) The two amino acids will not be separated.

9) According to the Henderson-Hasselbalch equation, when the concentrations of proton acceptor and proton donor are the same, then
   A) only salt forms are present.
   B) pKₐ = log[proton acceptor]/[proton donor].
   C) pH = pKₐ.
   D) the carboxylic acid is totally neutralized.

10) The primary structure of a protein describes the _______.
    A) Φ and Ψ angles for each amino acid
    B) number of each type of amino acid (percent composition)
    C) linear sequence of amino acids
    D) overall three-dimensional shape

11) The peptide bond is which of the following?
    A) an ester bond       B) an ether bond       C) an amide bond       D) an amine bond

12) What is the net charge on the dipeptide Arg-Pro at pH 9.0? The table below gives the pKₐ's of the ionizable groups on the free amino acids.

<table>
<thead>
<tr>
<th>Free amino acid</th>
<th>pKₐ of α-Carboxyl group</th>
<th>pKₐ of α-amino group</th>
<th>pKₐ of side chain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arginine</td>
<td>1.8</td>
<td>9.0</td>
<td>12.5</td>
</tr>
<tr>
<td>Proline</td>
<td>2.0</td>
<td>10.6</td>
<td>---</td>
</tr>
</tbody>
</table>

   A) 0       B) +0.5       C) +1       D) -1       E) -0.5

13) Which is used as the basis of separation of proteins by affinity chromatography?
    A) The net charge and pI of the protein at the pH of the column.
    B) The protein's molecular weight.
    C) The selective binding of the protein to a ligand on the column matrix.
    D) The protein's density.

14) The ________ is the single shape a protein adopts under physiological conditions.
    A) most stable enantiomer       B) minimal configuration
    C) primary structure              D) native conformation
15) What is the approximative molecular mass of a 200-amino acid protein.
   A) 20,000  B) 22,000  C) 11,000  D) 222,000  E) None of above

16) Structural proteins that typically assemble into large cables or threads to provide mechanical support to cells or organisms are classified as ________ proteins.
   A) enzyme  B) fibrous  C) globular  D) β-strand

17) What does it mean to say a protein is multimeric?
   A) In vivo it establishes an equilibrium between two or more active conformations.
   B) The active protein involves the association of two or more polypeptide chains.
   C) The protein has multiple α-helices.
   D) It has more than fifty amino acids.

18) Which statement is not true about the peptide bond?
   A) The peptide bond is longer than the typical carbon-nitrogen bond.
   B) Rotation is restricted about the peptide bond.
   C) The carbonyl oxygen and the amide hydrogen are most often in a trans configuration with respect to one another.
   D) The peptide bond has partial double-bond character.

19) Which represents the backbone of a protein?
   Note:  R = amino acid side chain
          N = nitrogen
          Cα = alpha carbon
          C = carbonyl carbon
   A) repeating units of N-Cα-C  B) repeating units of Cα-C
   C) repeating units of N-C  D) R1R2R3R4R5

20) Ramachandran determined the "allowed" values of the phi and psi angles primarily by considering ________.
   A) the hydropathy of amino acids  B) pKₐ values of the amino acids
   C) hydrogen bonding effects  D) steric hindrance

21) What would you expect about the formation of an α-helix for a segment of a protein chain that contains lysine approximately every fourth residue with all other residues being mostly hydrophobic?
   A) Helix formation would never occur regardless of pH.
   B) Helix formation would be favored at high pH.
   C) Helix formation would be favored at low pH.
   D) Helix formation would be favored at neutral pH.
22) Supersecondary structures that contain recognizable combinations of \( \alpha \)-helices, \( \beta \)-strands and loops (e.g. \( \beta \)-barrel) are called _______.

A) homologous regions  
B) folds  
C) domains  
D) motifs

23) Which of the following supersecondary structures corresponds to a Greek key.

![Greek key structures](image)

A)  
B)  
C)  
D)  
E) 

24) Which structure below indicates the proper hydrogen-bonding pattern between amino acids in an \( \alpha \)-helix? (Dashed lines represent the hydrogen bonds.)

A) I  
B) II  
C) III  
D) IV

25) The principle forces holding subunits of an oligomeric protein to each other are _______.

A) hydrophobic interactions  
B) disulfide bonds  
C) covalent bonds  
D) peptide bonds
26) _______ is used to estimate the molecular weight of oligomeric proteins, while _______ is used to determine the molecular weight of each chain.
   A) Melting point; SDS-gel electrophoresis
   B) Acrylamide gel electrophoresis; isoelectric focusing
   C) SDS-gel electrophoresis; NMR
   D) SDS-gel electrophoresis; gel-filtration chromatography
   E) Gel-filtration chromatography; SDS-gel electrophoresis

27) Hemoglobin is
   A) a dimer of subunits each with two myoglobin proteins.
   B) an erythrocyte.
   C) a tetramer of four globin chains and one heme prosthetic group.
   D) a tetramer of 4 myoglobin proteins.
   E) a dimer of subunits each with two distinct protein chains (alpha and beta).

28) Unlike typical catalyzed reactions in organic chemistry, enzyme reactions are
   A) usually stereospecific.
   B) modulated to change activity levels.
   C) reaction specific.
   D) essentially 100% efficient.
   E) All of the above

29) An enzyme that catalyzes conversions of L-amino acids to D-amino acids is called a/an _______.
   A) hydrolase
   B) isomerase
   C) synthase
   D) synthetase
   E) lyase

30) At the beginning of an enzyme-catalyzed reaction the _______ is negligible.
    A) disappearance of ES  B) formation of ES
    C) formation of E + P  D) conversion of ES to E + S

31) Which enzyme below is fastest?
    A) kinase, $k_{cat} = 10^3$
    B) catalase, $k_{cat} = 10^7$
    C) carboxypeptidase, $k_{cat} = 10^2$
    D) papain, $k_{cat} = 10$
32) The enzyme carbonic anhydrase catalyses the following reaction:

\[
\text{HCO}_3^- + \text{H}^+ \rightarrow \text{H}_2\text{O} + \text{CO}_2
\]

Bicarbonate

Given the following data for this reaction, determine the number of \( \text{CO}_2 \) molecules produced by the enzyme per second: \([\text{HCO}_3^-] = 3 \text{ mM} ; \) \( \text{Vmax: 0.12 moles/min} ; \) carbonic anhydrase: \( 5 \times 10^9 \) moles; \( \text{Km: 2.6} \times 10^{-2} \text{ M} \), reaction volume : 1 ml.

A) \( 4 \times 10^5 \text{ s}^{-1} \)  
B) \( 2.4 \times 10^7 \text{ s}^{-1} \)  
C) \( 6.67 \times 10^2 \text{ s}^{-1} \)  
D) \( 0.08 \text{ s}^{-1} \)

33) The (lower, higher) the value of \( \text{K}m \), the (less, more) tightly the enzyme is bound to the substrate.

A) lower, less  
B) lower, more  
C) higher, less  
D) higher, more  
E) B and C  
F) A and D

34) Which statement is true about the removal of reversible inhibitors from enzyme solutions?

A) Dialysis and gel filtration are often used.  
B) These inhibitors cannot be separated from the enzyme without treatment with diisopropylfluorophosphate.  
C) PAGE is the primary technique used for this purpose.  
D) Removal of reversible inhibitors is extremely difficult and can be achieved only after many purification steps.

35) Which equilibrium below applies to noncompetitive inhibition?

A) I  
B) II  
C) III  
D) IV
36) What type of inhibition is indicated by the data graphed below?

A) noncompetitive  B) competitive  
C) irreversible  D) uncompetitive

37) The following data were obtained in the presence and absence of inhibitor. What type of inhibition is shown?

<table>
<thead>
<tr>
<th>Substrate concentration (millimolar)</th>
<th>Rate without inhibitor (mmol/min)</th>
<th>Rate with inhibitor (mmol/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.100</td>
<td>2.5</td>
<td>1.6</td>
</tr>
<tr>
<td>0.200</td>
<td>4.2</td>
<td>2.9</td>
</tr>
<tr>
<td>0.500</td>
<td>6.6</td>
<td>5.1</td>
</tr>
<tr>
<td>0.750</td>
<td>7.4</td>
<td>6.2</td>
</tr>
</tbody>
</table>

A) uncompetitive  B) irreversible  
C) noncompetitive  D) competitive  
E) cannot tell inhibition type from the information given

38) What is the Ki value for the inhibitor shown in problem 37 if [inhibitor] = 0.01 mM?

A) 0.0045 mM  B) 0.0082 mM  
C) 0.022 mM  D) 0.012 mM
39) An enzyme is irreversibly inhibited by diisopropylfluorophosphate (DFP). What does this show?
A) Serine is likely an important residue in the active site.
B) The enzyme has been denatured by DFP.
C) DFP is an analog of the enzyme's substrate.
D) DFP is an allosteric modulator of the enzyme.

40) Two curves showing the rate versus substrate concentration are shown below for an enzyme-catalyzed reaction. One curve is for the reaction in the presence of substance X. The other curve is for data in the absence of substance X. Examine the curves and tell which statement below is false.

A) X is a competitive inhibitor.
B) The enzyme exhibits non-Michaelis-Menten kinetics.
C) X is an activator of the enzyme.
D) X is likely an allosteric modulator.

41) Replacement of the amino acid _______ at or near an active site of an enzyme is more likely to change enzyme activity than the replacement of _______ at or near the active site.
A) histidine; aspartate
B) histidine; leucine
C) leucine; histidine
D) leucine; isoleucine

42) Which amino acid is least likely to participate in acid-base catalysis?
A) histidine
B) aspartate
C) tyrosine
D) lysine

43) A histidine was determined to be the critical residue involved in an enzyme-catalyzed reaction. If the pK\textsubscript{a} of the histidine is known to be 6.5 in the active site and the pH of maximum catalytic activity is 7.2, what is likely the primary role of histidine in the catalytic reaction?
A) acts as a proton donor
B) reduces the entropy of the substrate
C) stabilizes a charged intermediate
D) forms a covalent bond with the substrate
44) The role of serine at the active site of serine proteases is to act as a(n) _______ catalyst, while the histidine residue serves as a(n) _______ catalyst.
   A) weak; strong
   B) covalent; acid-base
   C) strong; weak
   D) anionic; ionic
   E) acid-base; covalent

45) The catalytic triad of chymotrypsin and other serine proteases consists of
   A) three amino acid residues adjacent in the primary structure which act to make serine a strong nucleophile.
   B) three amino acid residues close enough in space to make serine a strong nucleophile.
   C) three enzymes with very similar structural features.
   D) three subunits of the enzyme.
   E) None of the above.

46) Inhibition of ATCase by a ______ nucleotide and activation of ATCase by a ______ nucleotide keep the balance of purine and pyrimidine pools in E. coli.
   A) purine; purine
   B) pyrimidine; pyrimidine
   C) purine; pyrimidine
   D) pyrimidine; purine

47) Which are purines?
   A) adenine and thymine
   B) uracil and guanine
   C) cytosine and thymine
   D) guanine and adenine

48) Which of the following is guanine?

   A
   B
   C
   D

49) ATP is not a nucleoside because it ______.
   A) is not connect to a carbohydrate group
   B) has three phosphates instead of just one
   C) lacks the deoxyriboseyl group
   D) has phosphate groups

50) In DNA, phosphodiester bonds form with hydroxyl groups of carbons number ______ and ______ of each deoxyribose sugar.
   A) 3'; 5'
   B) 2'; 4'
   C) 2'; 3'
   D) 4'; 5'
   E) 3'; 4'
51) Much of the stability of the double-stranded DNA structure is the result of
   A) the angle of the planes of the bases with respect to the helix axis.
   B) hydrogen bonding between purines.
   C) the stacking interactions between adjacent base pairs.
   D) the phosphodiester backbone.

52) The rise and pitch of B-DNA are 0.33 nm and 3.40 nm, respectively. About how many helical
   turns are there in a fragment 1 mm in length?
   A) 330
   B) 3030
   C) 294
   D) 0.0034
   E) Cannot calculate from the information given.

53) Regions of DNA that are most easily unwound have
   A) greater A:T content.  B) about half G and half C.
   C) greater G:C content.  D) alternating A and G.

54) In proteins, amino acids are linked by peptide bonds; in polynucleotides, nucleotides are linked
   by
   A) phosphoanhydride bonds.
   B) 5’-3’phosphodiester bonds.
   C) 3’-5’phosphodiester bonds
   D) All of the above.

55) "Five prime to three prime" description of a DNA strand refers to
   A) the location of the hydroxyl groups.
   B) the phosphorylated 5’ carbon on one sugar and the 3’ carbon on the next sugar.
   C) the phosphorylated 5’ carbon at one end, the 3’ at the other end.
   D) the phosphodiester backbone of DNA.

56) As B-DNA is gradually heated, the absorbance at 260 nm
   A) stays the same.
   B) decreases.
   C) is half way between that of poly (AT and poly (GC).
   D) increases.

57) Which is not a difference between B-DNA and A-DNA?
   A) Both are helical, but B-DNA is right-handed and A-DNA is left-handed.
   B) For polynucleotide strands containing the same number of nucleotides, the A-DNA strand
      will be shorter from end-to-end than the corresponding B-DNA.
   C) A-DNA forms under more dehydrating conditions than B-DNA.
   D) The planes of the nitrogenous bases are not perpendicular to the helix axis in A-DNA.
58) Which is **not** a difference between RNA and DNA?
   A) RNA is single-stranded; DNA is double-stranded.
   B) The sugar ring of RNA is more oxidized than that in DNA.
   C) RNA cannot form helices.
   D) RNA contains uracil; DNA usually does not.

59) Which of the following represents correctly paired bases:

![Diagram of nucleotides]

A) ![Diagram A]  
B) ![Diagram B]  
C) ![Diagram C]  
D) ![Diagram D]

60) DNA that has been liberally labeled with radioactive $^{14}$C is used as the template for replication. Replication is carried out in a medium containing only **unlabeled** nucleotides. After two rounds of replication, what percent of DNA molecules are still labeled?
   A) 25%  
   B) 50%  
   C) 75%  
   D) 100%

61) Meselson and Stahl’s experiments involved growing *E. coli* on a medium containing $^{15}$N (heavy nitrogen) which increased the density of the bacterial DNA. Cells were then grown on a medium containing only $^{14}$N. DNA samples were obtained for analysis after one, two and three rounds of replication (generations) and centrifuged on a density gradient. The double-helical DNA forms bands in the gradient depending on its density. How many bands did Meselson and Stahl see after two generation of cells were grown on the $^{14}$N medium?
   A) Two, one with DNA containing both $^{15}$N and $^{14}$N and one with DNA containing only $^{14}$N.  
   B) Two, one with DNA containing only $^{15}$N and one with DNA containing only $^{14}$N.  
   C) Three, one with DNA containing only $^{15}$N, one with DNA containing both $^{15}$N and $^{14}$N and one with DNA containing only $^{14}$N.  
   D) One with DNA containing both $^{15}$N and $^{14}$N.

62) Which of the following would be the best primer for replicating in its entirety the following DNA strand:

$5' TAGATAGCTAGATCGCATCCTATCGATATCGGATATCCTTATCTATCGGACG 3'$

A) TAGATAGCTAGATG  
B) CGCTCCGATAGATA  
C) TATCTATCGGACG  
D) CATCTAGCTATCTA
63) What is the melting point (Tm) of the following dsDNA molecule?

\[
\begin{align*}
&\text{CATCTAGCTATCTA} \\
&\text{GTAGATCGATAGAT}
\end{align*}
\]

A) 38°C  B) 46°C  C) 76°C  D) 92°C

64) DNA polymerase III requires a/an _______ for synthesis of DNA to occur.

A) RNA primer  B) DNA template  C) free 3'-OH end of a DNA strand  D) All of the above

65) The processivity of E. coli DNA polymerase III holoenzyme accounts for all of the following except

A) the directionality of polymerization.
B) the relatively small number of enzymes needed to replicate the entire chromosome.
C) the rapid rate of polymerization.
D) the ability of a single holoenzyme to add many nucleotides to a growing DNA chain.

66) The RNA primer at the beginning of each Okazaki fragment is removed by

A) DNA polymerase I.  B) DNA polymerase II.  C) DNA polymerase III.  D) 3' → 5' exonuclease subunit of DNA polymerase III.

67) Okazaki fragments are _______.

A) short stretches of DNA formed on the lagging strand
B) the smallest subunits of DNA polymerase III
C) fragments of DNA polymerase I that lack 5' → 3' exonuclease activity
D) short RNA primers needed for initiation of polymerization

68) What is a reasonable length for an RNA primer in E. coli?

A) a few nucleotides  B) 50 nucleotides  C) 100 nucleotides  D) 1000 nucleotides

69) Fragments on the lagging strand are joined by the enzyme _______.

A) DNA ligase  B) DNA primase  C) DNA polymerase I  D) DNA synthase

70) The technique of Southern blot is used to probe ________

A) Nucleic acids  B) DNA  C) Proteins  D) RNA
MULTIPLE CHOICE – SECTION B
Choose the one right answer from the choices provided. 10 marks per question.

71) You wish to determine the sequence of a short peptide. You digest the peptide with the following reagents and obtain the results shown below:

1) HCl hydrolysis: A, D, I, K, M, S, T, V, W
2) FDNB digestion: A
3) Carboxypeptidase: T
4) Trypsin: a) A, D, K, M, S
   b) I, T, V, W
5) Cyanogen Bromide: a) A, M
   b) D, I, K, S, T, V, W
6) Cutting fragment (5b) with FDNB yields: S
7) Thermolysin: a) V
   b) W
   c) L, T
   d) A, D, K, M, S
8) Chymotrypsin: a) I, T
   b) A, D, K, M, S, V, W

How many amino acids would be found in each of the fragments obtained after cutting this peptide with protease V8:

A) 4 and 5  C) 2 and 7
B) 3 and 6  D) protease V8 would not cut this peptide

72) The table shown below presents data obtained during the purification of lactate dehydrogenase. Which purification step worked best (Note: extinction coefficient of NADH= $6.22 \times 10^3$ M$^-1$cm$^-1$)?

<table>
<thead>
<tr>
<th>Purification Step</th>
<th>Volume (mL)</th>
<th>Dilution</th>
<th>Absorbance NADH @ 340 nm (1 min reaction)</th>
<th>Protein concentration (mg/mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homogenate</td>
<td>10</td>
<td>1/100</td>
<td>0.323</td>
<td>33.02</td>
</tr>
<tr>
<td>Supernatant after 40% salt precipitation</td>
<td>8.9</td>
<td>1/100</td>
<td>0.316</td>
<td>31.84</td>
</tr>
<tr>
<td>Gel filtration chromatography</td>
<td>9.1</td>
<td>1/100</td>
<td>0.274</td>
<td>26.51</td>
</tr>
<tr>
<td>Ion exchange chromatography</td>
<td>5</td>
<td>1/100</td>
<td>0.345</td>
<td>12.07</td>
</tr>
</tbody>
</table>

A) Gel filtration                  C) salt precipitation
B) Ion exchange                   D) the purification did not work
TRUE/FALSE. Select 'A' if the statement is true and 'B' if the statement is false. 2 marks per question.

73) The isoelectric point of amino acids is the average of the values $pK_{a\text{COOH}} + pK_{a\text{NH}_2}$.

74) In gel electrophoresis the molecules with the highest molecular weight migrate the farthest from the starting wells.

75) Most proteins contain an approximately equal amount of each of the standard amino acids.

76) The twenty standard amino acids are the only amino acids found in living organisms.

77) All proteins possess primary, secondary, tertiary and quaternary structure.

78) Once denatured, proteins cannot be renatured or restored to the native state.

79) Ascorbic acid is necessary for the formation of hydroxyproline and hydroxylysine residues before they are incorporated into the collagen protein molecule.

80) The porphyrin prosthetic group is held into the interior of globin molecules by covalent bonds to specific amino acid residues.

81) Increasing the concentration of a classic competitive inhibitor has no effect on the maximum velocity of an enzyme-substrate reaction.

82) Allosteric modulators bind covalently to the regulatory site of an enzyme and change its conformation.

83) The two strands of double-stranded DNA have the same content of each of the bases A, T, G and C.

84) The major and minor grooves are the same in B-DNA and A-DNA.

85) RNA does not have a double strand form.

86) The $\beta$ subunits of *E. coli* DNA polymerase form a sliding clamp that surrounds the DNA strands at the replication fork.
87) In *E. coli* replication begins at the origin of replication and proceeds in one direction until the entire circular DNA molecule has been copied.

88) DNA ligase enzymes use ATP as a cofactor.

89) In DNA sequencing, reading from the bottom towards the top of the gel will give you the sequence in the 3’→5’ orientation.

**ESSAY QUESTION.** Provide a complete answer to the following question. Write your answer on this questionnaire, limiting yourself to the space allotted. For 26 marks.

90) Explain why DNA replication can only occur in the 5’→3’ direction and not in the 3’→5’ direction.

Continues on following page
Question 90 (continued)
<table>
<thead>
<tr>
<th>Amino acid</th>
<th>pK&lt;sub&gt;a&lt;/sub&gt; value</th>
<th>Carboxyl group</th>
<th>Amino group</th>
<th>Side chain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glycine</td>
<td>2.4</td>
<td>9.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alanine</td>
<td>2.4</td>
<td>9.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valine</td>
<td>2.3</td>
<td>9.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leucine</td>
<td>2.3</td>
<td>9.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Isoleucine</td>
<td>2.3</td>
<td>9.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methionine</td>
<td>2.1</td>
<td>9.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proline</td>
<td>2.0</td>
<td>10.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phenylalanine</td>
<td>2.2</td>
<td>9.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tryptophan</td>
<td>2.5</td>
<td>9.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Serine</td>
<td>2.2</td>
<td>9.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Threonine</td>
<td>2.1</td>
<td>9.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Amino acid</th>
<th>pK&lt;sub&gt;a&lt;/sub&gt; value</th>
<th>Carboxyl group</th>
<th>Amino group</th>
<th>Side chain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cysteine</td>
<td>1.9</td>
<td>10.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tyrosine</td>
<td>2.2</td>
<td>9.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asparagine</td>
<td>2.1</td>
<td>8.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glutamine</td>
<td>2.2</td>
<td>9.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aspartic acid</td>
<td>2.0</td>
<td>9.9</td>
<td>3.9</td>
<td></td>
</tr>
<tr>
<td>Glutamic acid</td>
<td>2.1</td>
<td>9.5</td>
<td>4.1</td>
<td></td>
</tr>
<tr>
<td>Lysine</td>
<td>2.2</td>
<td>9.1</td>
<td>10.5</td>
<td></td>
</tr>
<tr>
<td>Arginine</td>
<td>1.8</td>
<td>9.0</td>
<td>12.5</td>
<td></td>
</tr>
<tr>
<td>Histidine</td>
<td>1.8</td>
<td>9.3</td>
<td>6.0</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.2: pK<sub>a</sub> values of acidic and basic constituents of free amino acids at 25°C

Table 3-2 Principles of Biochemistry, 4/e © 2006 Pearson Prentice Hall, Inc.