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Thermodynamic properties of enzyme-catalyzed reactions involving guanine, xanthine, and their nucleosides and nucleotides

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Abstract

The standard Gibbs energies of formation of species in the guanosine triphosphate and the xanthosine triphosphate series have been calculated on the basis of the convention that the standard Gibbs energy of formation for the neutral form of guanosine is equal to zero in aqueous solution at 298.15 K and zero ionic strength. This makes it possible to calculate apparent equilibrium constants for a number of enzyme-catalyzed reactions for which apparent equilibrium constants have not been measured or cannot be measured directly because they are too large. The eventual elimination of this convention is discussed. This adds ten reactants to the database BasicBiochemData3 that has 199 reactants. The standard transformed Gibbs energies of formation of these ten reactants are used to calculate apparent equilibrium constants at 298.15 K, 0.25 M ionic strength, and pHs 5, 6, 7, 8, and 9. The p*K*s, standard Gibbs energies of hydrolysis, and standard Gibbs energies of deamination are given for the reactants in the ATP, IMP, GTP, and XTP series.

Keywords: Guanine; Xanthine; Guanosine triphosphate; Xanthine triphosphate; Thermodynamics; Apparent equilibrium constants

1. Introduction

The extensive studies of the thermodynamics of hydrolysis in the ATP series prior to 1992 made it possible to calculate the standard transformed Gibbs energies of formation $\Delta_f G'^\circ$ of these reactants and the apparent equilibrium constants of five enzyme-catalyzed reactions at 298.15 K, pH 7, pMg 3, and ionic strength $I=0.25$ M [1]. These calculations could have been extended to other pHs, pMgs, and ionic strengths. In order to calculate $\Delta_f G'^\circ$ of these reactions, it was necessary to adopt the convention that $\Delta_f G^\circ=0$ for the neutral form of adenosine in aqueous solution. However, when Boerio-Goates et al. [2] determined the third law entropy of adenosine and added to the knowledge of its enthalpy [3], it became possible to calculate $\Delta_f G^\circ$ of adenosine and all the other species in the ATP series in aqueous solution with respect to the elements in their reference states. A convention of the table of species properties in BasicBiochemData3 [4] is that $\Delta_f G^\circ=\Delta_f H^\circ=0$ for coA^-, FAD_{ox}^{2-}, $FADenz^{2-}$, $cytochrome^{3+}$, $ferredoxin_{ox}^{4-}$, FMN^{2-}, $glutathione_{ox}^{2-}$, NAD_{ox}^-, $NADP_{ox}^{3-}$, $thioredoxin_{ox}^0$, and $ubiquinone_{ox}^0$. The disadvantage of these conventions is that the properties of these reactants cannot be used to calculate the thermodynamic properties of reactions forming these species from the elements. On the other hand, correct values of apparent equilibrium constants and standard transformed enthalpies of reaction can be calculated on the basis of these conventions for many enzyme-catalyzed reactions involving these reactants. The requirement for these calculations is that moities of these reactants must appear on both sides of the catalyzed reactions.

In 2005 Boeiro-Goates et al. [5] determined the third law entropy and enthalpy of formation of inosine, and this made it possible to calculate the standard Gibbs energies of formation and standard enthalpies of formation of all the species in the ITP series. In making these calculations they utilized the structural similarities of the ITP series and ATP series to estimate the thermodynamic properties of all the species. In calculating standard thermodynamic properties in the ITP series, Boeiro-Goates and coworkers pointed out that "there are significant structural similarities between the inosine 5′-phosphate series and the adenosine 5′-phosphate series." They go on to say that "on the basis of structural similarity one would expect that the p*K*s and $\Delta_r H^\circ$ values for the H^+(aq) and Mg^{2+}(aq) binding

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reactions involving the corresponding phosphate groups in the inosine 5′-phosphate series and the adenosine 5′-phosphate series to have essentially the same value." These comments apply to the deamination reactions as well. This has made it possible to calculate the apparent equilibrium constants of many enzyme-catalyzed reactions involving members of the ITP series [6].

The reactions that connect the ATP series and the ITP series and the reactions that connect the GTP series and the XTP series are represented schematically in Eq. (1), which is related to Figures 28–23 and 28–30 in Voet and Voet [7]. The reactions in the vertical direction are hydrolysis reactions, but the

ATP	=	ITP		GTP	=	XTP
‖		‖		‖		‖
ADP	=	IDP		GDP	=	XDP
‖		‖		‖		‖
AMP	=	IMP		GMP	=	XMP
‖		‖		‖		‖
adenosine	=	inosine		guanosine	=	xanthosine
‖		‖		‖		‖
adenine	=	hypoxanthine		guanine	=	xanthine

(1)

H_2O and other reactants are not shown. The reactions in the horizontal direction are deaminase reactions, but the H_2O and other products are not shown.

This article provides calculations of the standard Gibbs energies of formation of species of hypoxanthine, the guanosine triphosphate series and the xanthosine triphosphate series. The $\Delta_fG°$ in the GTP and XTP series are based on the convention that $\Delta_fG°$(guanosine, aq, 298.15 K, I=0)=0. The apparent equilibrium constants for the reactions in the GTP and XTP series that are indicated by equal signs can be calculated at 298.15 K, ionic strengths from zero to about 0.35 M, and pHs in the range 5 to 9. The apparent equilibrium constants are not presented for all of these reactions, but tables are given of reactions for the GTP series and the UTP series with their EC numbers [8] to show that apparent equilibrium constants can be calculated using BasicBiochemData3 [4].

The species database contains data on the species of 199 reactants. For 105 of these reactants only standard transformed Gibbs energies of formation and average numbers of hydrogen atoms a 298.15 K can be calculated. For 94 of the reactants, standard enthalpies of formation of species are known, and so standard transformed Gibbs energies, standard transformed enthalpies, standard transformed entropies, and average numbers of hydrogen atoms can be calculated as functions of temperature, pH, and ionic strength. Loading this package also makes available functions of temperature, pH, and ionic strength for these 199 reactants. This makes it easy to calculate apparent equilibrium constants and other properties of many more reactants than it took to make the table.

The thermodynamic properties of species in the guanosine triphosphate series are similar to those in the adenosine triphosphate series and the inosine triphosphate series, but there is a difference in the pKs for the purine rings (4.19 for adenine, 8.9 for hypoxanthine, 9.2 for guanine, and 7.4 for xanthine at 298.15 K and zero ionic strength), according to Dawson et al. [9]. More background on pKs is given by Ts'o [10]. It is assumed here that the pKs for the phosphate dissociations in the GTP series and the XTP series are the same as in the ITP series. It is also assumed that the $\Delta_rG°$ for the hydrolysis reactions in the GTP series and the XTP series are the same as in the ITP series. The thermodynamic connection between the ATP series and the ITP series was provided by the fact that the thermodynamic properties of adenosine and inosine are both known with respect to the elements in their reference states. The thermodynamic connection between the GTP series and the XTP series is provided here by the assumption that $\Delta_rG°$ for the deamination of quanosine is equal to the $\Delta_rG°$ for the deamination of adenosine. However, as indicated by Eq. (1), it is currently not possible to connect the thermodynamics of the ATP/ITP series with the GTP/XTP series.

2. Calculation of the standard Gibbs energies of formation of the species of hypoxanthine

The properties of the species of hypoxanthine are needed to complete the ITP series. The entry for hypoxanthine in BasicBiochemData3 is incorrect because properties of just the uncharged species are given. The data in BasicBiochemData3 make it possible to calculate $\Delta_rG°$(298.15 K, I=0) for the following four chemical reactions:

$$ATP^{4-} + H_2O = IDP^{4-} + NH_3 \quad \Delta_rG° = -4.11 \text{ kJ mol}^{-1} \tag{2}$$

$$ADP^{3-} + H_2O = IDP^{3-} + NH_3 \quad \Delta_rG° = -4.19 \text{ kJ mol}^{-1} \tag{3}$$

$$AMP2^{-} + H_2O = IMP^{2-} + NH_3 \quad \Delta_rG° = -4.28 \text{ kJ mol}^{-1} \tag{4}$$

$$\text{Adenosine}^0 + H_2O = \text{inosine}^0 + NH_3 \quad \Delta_rG° = -3.98 \text{ kJ mol}^{-1} \tag{5}$$

These values are nearly the same, but the last reaction is more like

$$\text{Adenine}^0 + H_2O = \text{hypoxanthine}^0 + NH_3 \tag{6}$$

and so $\Delta_rG°$ for reaction 6 is assumed to be −3.98 kJ mol^{-1}. This leads to $\Delta_fG°$(hypoxanthine^0, 298.15 K, I=0)=98.75 kJ mol^{-1}. The use of pK(hypoxanthine, 298.15 K, I=0)=8.90 leads to $\Delta_fG°$(hypoxanthine^{-1}, 298.15 K, I=0)=149.55 kJ mol^{-1}. The apparent equilibrium constants for these five deamination reactions at five pHs are given in the Appendix.

In BasicBiochemData3 [4], small matrices of the form $\{\{\Delta_fG°_1, \Delta_fH°_1, z_1, N_{H1}\}, \{\Delta_fG°_2, \Delta_fH°_2, z_2, N_{H2}\}, \ldots\}$, where species 1 is the most basic species, are used to store data on reactants (sums of species). Therefore, hypoxanthine$_{sp}$= {{149.55,_,−1,3},{98.75,_,0,4}}. This makes it possible to calculate the apparent equilibrium constants K ' of adenine+ H_2O=hypoxanthine+ammonia at 298.15 K, pHs in the range 5 to 9, and ionic strengths in the range zero to about 0.35 M.

An experimental value of K' for adenosine+H_2O=inosine +ammonia at pH 7.5 and 0.10 M ionic strength was reported by

Table 1
Some of the standard Gibbs energies of formation in the ITP series at 298.15 K and zero ionic strength (the charges of the species are shown in parentheses) [5]

Reactant	$\Delta_f G°$(kJ mol^{-1})	
ITP	−2982.90(−4)	−3026.28(−3)
IDP	−2121.01(−3)	−2161.99(−2)
IMP	−1255.42(−2)	−1293.84(−1)
Inosine	−409.15(0)	
Hypoxanthine	98.75(0)	

Wolfenden [11] to be 1175. Use of the Mathematica program calckprime [12] yields 300. However, the values of apparent equilibrium constants based on the third law measurements on inosine [4] are believed to be more accurate. It is experimentally difficult to determine apparent equilibrium constants as large as 1175 directly.

3. Calculation of standard Gibbs energies of formation of the species in the GTP series

Since it is currently not possible to connect species in the GTP series with the elements in their reference states, $\Delta_f G°$ (guanosine^0, 298.15 K, I=0) is taken to be zero. Since the GTP series is like the ITP series, the $\Delta_f G°$ calculated by Boeiro-Goates et al. [4] for the ITP series can be used to calculate some of the $\Delta_f G°$ in the GTP series. The $\Delta_f G°$ of the two more acidic species of ITP, IDP, and IMP and the electrically neutral species of inosine and hypoxanthine are given in Table 1, where the electric charges on the species are shown.

In this step of the calculation of the standard Gibbs energies of formation in the guanosine series, the more basic species are not yet included because the pKs of the guanine rings are different from the pKs of the hypoxanthine ring. Table 1 can be used to calculate the pKs for the following acid dissociations of the inosine phosphates at 298.15 K and zero ionic strength:

$$ITP^{3-} = H^+ + ITP^{4-} \quad pK = 7.60 \tag{7}$$

$$IDP^{2-} = H^+ + IDP^{3-} \quad pK = 7.18 \tag{8}$$

$$IMP^{-} = H^+ + IMP^{2-} \quad pK = 6.73 \tag{9}$$

It is assumed that these pKs also apply to the GTP series.

Because of the similarity of the ITP series and the GTP series and the currently necessary convention that $\Delta_f G°$(guanosine^0, 298.15 K, I=0)=0, 409.15 kJ mol^{-1} is added to all the entries in Table 1 to obtain the values in Table 2 for the standard Gibbs energies of formation of species in the GTP series. This does not change the $\Delta_r G°$ of chemical reactions that can be calculated from Table 1.

Table 2
Standard Gibbs energies of formation at 298.15 K and zero ionic strength in the GTP series based on the convention that $\Delta_f G°$(guanosine, 298.15 K, I=0)=0

Reactant	$\Delta_f G°$(kJ mol^{-1})	
GTP	−2573.75(−4)	−2617.13(−3)
GDP	−1711.86(−3)	−1752.84(−2)
GMP	−846.27(−2)	−884.69(−1)
Guanosine	0(0)	
Guanine	507.90(0)	

Table 3
Thermodynamic properties of the species in the GTP series at 298.15 K and zero ionic strength

Reactant	$\Delta_f G°$(kJ mol^{-1})	z	N_H
GTP	−2514.24	−5	11
	−2573.75	−4	12
	−2617.13	−3	13
GDP	−1655.41	−4	11
	−1711.86	−3	12
	−1752.84	−2	13
GMP	−789.59	−3	11
	−846.27	−2	12
	−884.69	−1	13
Guanosine	52.86	−1	12
	0	0	13
Guanine	560.41	−1	4
	507.90	0	5

Table 2 is incomplete because it does not contain the $\Delta_f G°$ of the more negatively charged species produced in the dissociation of the acidic group of the purine ring. The ring pK of guanine is 9.2 [9], compared with 8.9 for hypoxanthine, as mentioned in Section 2. Therefore, the ring pKs in the GTP series are all taken to be 0.30 higher than in the inosine series. The ring pKs in the GTP series can be used to calculate $\Delta_f G°$ of the more negatively charged species in the GTP series. The ring pKs in the GTP series are as follows: GTP (10.40), GDP (9.89), GMP (9.93), guanosine (9.26), and guanine (9.20). This yields the species data in Table 3 that can be used to calculate standard transformed Gibbs energies of formation at 298.15 K, pHs in the range 4 to 9, and ionic strengths in the range zero to about 0.35 M. The charge on the species is z, and the number of hydrogen atoms it contains is N_H.

4. Calculation of standard Gibbs energies of formation of species in the XTP series

The calculation of $\Delta_f G°$ for the species in the XTP series uses the same steps as the calculation of $\Delta_f G°$ for the species

Table 4
Thermodynamic properties of the species in the XTP series at 298.15 K and zero ionic strength

Reactant	$\Delta_f G°$(kJ mol^{-1})	z	N_H
XTP	−2739.37	−5	10
	−2788.40	−4	11
	−2831.78	−3	12
XDP	−1880.50	−4	10
	−1926.51	−3	11
	−1967.49	−2	12
XMP	−1014.51	−3	10
	−1060.92	−2	11
	−1099.34	−1	12
Xanthosine	−172.07	−1	11
	−214.65	0	12
Xanthine	335.49	−1	3
	293.25	0	4

Table 5
pKs and $\Delta_r G°$ of chemical reactions at 298.15 K and zero ionic strength in the ATP, ITP, GTP, and XTP series

Reactant	pK_1	pK_2	$\Delta_r G°$(hydrolysis)	$\Delta_r G°$(deamination)
ATP	7.60	4.68	−38.14	−4.11
ADP	7.18	4.36	−34.43	−4.19
AMP	6.73	4.00	−12.96	−4.28
Adenosine	3.47		−6.91	−3.96
Adenine	4.20			−3.96
ITP	10.09	7.60	−38.22	
IDP	9.56	7.18	−34.52	
IMP	9.63	6.73	−12.64	
Inosine	8.96		−6.91	
Hypoxanthine	8.90			
GTP	10.43	7.60	−38.22	−3.96
GDP	9.89	7.18	−34.52	−3.96
GMP	9.93	6.73	−12.64	−3.96
Guanosine	9.26		−6.91	−3.96
Guanine	9.20			−3.96
XTP	8.59	7.60	−38.22	
XDP	8.06	7.18	−34.52	
XMP	8.13	6.73	−12.64	
Xanthosine	7.46		−6.91	
Xanthine	7.40			

in the GTP series, except that first it is necessary to obtain $\Delta_f G°$(xanthosine^0, aq, 298.15 K, I=0) following the convention that $\Delta_f G°$(guanosine^0, aq, 298.15 K, I=0)=0. This is done on the assumption that the following reaction has the same equilibrium constant as reaction 5 at 298.15 K and zero ionic strength.

$$\text{Guanosine}^0 + H_2O = \text{xanthosine}^0 + NH_3 \quad \Delta_r G° = -3.96 \text{ kJ mol}^{-1} \tag{10}$$

Since $\Delta_f G°$(guanosine^0, aq, 298.15 K, I=0)=0, $\Delta_f G°$(xanthosine^0, aq, 298.15 K, I=0)=−214.65 kJ mol^{-1}. Since pK(xanthosine, 298.15 K, I=0)=7.46, the species matrix for xanthosine is given by xanthosinesp={{−172.07,_,−1,11}, {−214.65,_,0,12}}. This species matrix can be tested by calculating $\Delta_r G°$ for reaction 10 and the pK for xanthosine.

The standard Gibbs energies of formation in the GTP series given in Table 2 contain the information required to calculate the pKs for the phosphate groups in the XTP series, but 214.65 kJ mol^{-1} has to be subtracted from each of the entries in Table 2 to obtain the $\Delta_f G°$ for the XTP series. This adjusted Table 2 is incomplete because it does not contain $\Delta_f G°$ for the more negative species produced by the acid dissociation of the xanthine ring. The pK for xanthine is 7.4 at 298.15 K and zero ionic strength [9]. It is assumed that the ring pKs in the XTP series follow the pattern of the ITP series: XTP (8.59), XDP (8.06), XMP (8.13), xanthosine (7.46), and xanthine (7.40). This yields the species data in Table 4 that can be used to calculate standard transformed Gibbs energies of formation at 298.15 K, pHs in the range 4 to 9, and ionic strengths in the range zero to about 0.35 M. The functions of pH and ionic strength that give $\Delta_f G°$ can be calculated using calcdGmat.

5. Checking the properties of species in the GTP and XTP series

The species properties calculated in the preceding two sections can be checked by calculating three types of equilibrium constants and comparing them with previously published values of these properties in the ATP and ITP series: acid pKs, standard Gibbs energies of hydrolysis reactions, and standard Gibbs energies of deaminase reactions. These values are given in Table 5.

The pKs were calculated using the Mathematica program calcpK [12]. The pKs are numbered from the highest to the

Table 6
Apparent equilibrium constants for enzyme-catalyzed reactions involving the GTP series at 298.15 K, five pHs and 0.25 M ionic strength

	pH 5	pH 6	pH 7	pH 8	pH 9
EC 2.4.2.15 Guanosine phosphorylase					
guanine+ribose 1-phos=guanosine+Pi	2.3×10^3	1.7×10^3	9.2×10^3	7.3×10^2	6.7×10^2
EC 2.7.1.30 Glycerol kinase					
GTP+glycerol=GDP+glycerol 3-phos	4.5×10^5	8.0×10^5	4.7×10^6	4.7×10^7	6.1×10^8
EC 2.7.1.40 Pyruvate kinase					
GDP+phosphoenolpyruvate=GTP+pyruvate	1.1×10^6	6.1×10^5	1.1×10^5	1.1×10^4	8.4×10^2
EC 2.7.1.86 NADred kinase					
GTP+NAD_{red}=GDP+$NADP_{red}$	3.5	38.0	450	5.1×10^3	6.6×10^4
EC 2.7.1.143 Diphosphate-purine nucleoside kinase					
pyrophos+guanosine=Pi+GMP	26	23	45	210	480
EC 2.7.1.146 GDP specific phosphofructokinase					
GDP+fructose 6-phos=GMP+fructose-1,6-phos	62	410	5.3×10^3	5.2×10^4	3.8×10^5
EC 2.7.4.8 Guanylate kinase					
ATP+GMP=ADP+GDP	2.3	2.3	2.2	2.4	3.4
EC 2.7.4.10 Nucleotide-triphosphate-adenylate kinase					
GTP+AMP=GDP+ADP	2.6	2.5	2.4	2.6	3.3
EC 3.2.2.1 Purine nucleosidase					
guanosine+H_2O=guanine+ribose	16.2	16.2	16.3	16.5	17.5
EC 3.6.1.42 Guanosine-diphosphatase					
GDP+H_2O=GMP+Pi	2.2×10^5	2.9×10^5	9.1×10^5	6.5×10^6	4.5×10^7
EC 3.6.5.2 Small monomeric GTPase					
GTP+H_2O=GDP+Pi	5.3×10^5	6.8×10^5	2.1×10^6	1.7×10^7	2.1×10^8

lowest in the pH range 5 to 9. The p*K*s in the ITP series are from Boeiro-Goates et al. [5]. They are the same as in the ATP series and are assumed to be the same as in the GTP and XTP series. The purine group in the ATP series has values from 3.47 to 4.68. Since the acid groups in the purine rings in the GTP and XTP series are more like those in the ITP series, than the ATP series, the changes in these p*K*s are assumed to have the shifts found in the ITP series. The $\Delta_r G°$(phosphate hydrolysis) in the GTP series and XTP series have been taken to be the same as in the ITP series. The chemical reactions for phosphate hydrolysis have been written as follows:

$$ATP^{4-} + H_2O = ADP^{3-} + H_2PO_4^- \quad (11)$$

$$ADP^{3-} + H_2O = AMP^{2-} + H_2PO_4^- \quad (12)$$

$$AMP^{2-} + H_2O = adenosine^0 + HPO_4^{2-} \quad (13)$$

$$adenosine^0 + H_2O = adenine^0 + ribose. \quad (14)$$

The deamination reactions have been written as follows:

$$ATP^{4-} + H_2O = ITP^{4-} + NH_3 \quad (15)$$

$$GTP^{4-} + H_2O = XTP^{4-} + NH_3 \quad (16)$$

Note that the species of ITP and XTP series are the ones in which the ring binds a hydrogen ion so that the ions on the two sides of the reaction have the same charge.

6. Applications of standard transformed Gibbs energies of formation of reactants in the GTP series

The functions of pH and ionic strength that yield $\Delta_f G'°$ at 298.15 K of the reactants in the GTP series can be calculated using calcdGmat [12] and calckprime [12]. These functions of pH and ionic strength can be used to calculate apparent equilibrium constants for a number of enzyme-catalyzed reactions for which apparent equilibrium constants have not been measured. The apparent equilibrium constants for eleven enzyme-catalyzed reactions are given in Table 6. This is not a complete list of reactions involving the GTP series.

7. Applications of standard transformed Gibbs energies of formation of reactants in the XTP series

The functions of pH and ionic strength that yield the standard transformed Gibbs energies of formation of the reactants at 298.15 K in the XTP series make it possible to calculate apparent equilibrium constants for a number of enzyme-catalyzed reactions that involve only the xanthine moiety or the xanthine and guanosine moieties on both sides of the reaction. Apparent equilibrium constants for seven enzyme-catalyzed reactions are given in Table 7. This list is not complete.

8. Discussion

These calculations of standard Gibbs energies of formation of species in the GTP series and the XTP series are based on the similarities in the thermodyamic properties of the various purines, their nucleosides, and their nucleotides. It is assumed that the p*K*s of the phosphate groups shift with phosphorylation in the same way as in the ATP series. It is further assumed that the p*K*s of the purine rings shift within a series in the same way as in the ITP series. It is also assumed that the standard Gibbs energies of reaction of the chemical reactions of hydrolysis within the GTP and XTP series are the same as in the ITP series. Since the standard Gibbs energies of chemical reactions for the deamination reactions of ATP series are nearly the same, it is assumed that in the GTP series they are the same. The pH dependencies of the apparent equilibrium constants for enzyme-catalyzed reactions involving the GTP and XTP series are different because of the differences between the ring p*K*s. The convention that $\Delta_f G°$(guanosine^0, 298.15K, I=0)=0 makes it possible to calculate apparent equilibrium constants for many reactions that have not been studied experimentally. However, it is not yet possible to calculate apparent equilibrium constants for reactions in which the xanthine moiety is converted to the hypoxanthine moiety or the adenine moiety, or the guanine moiety is converted to the hypoxanthine moiety or adenine moiety. The following are examples

Table 7
Apparent equilibrium constants for enzyme-catalyzed reactions involving the XTP series at 298.15 K, five pHs and 0.25 M ionic strength

Biochemical reaction	pH 5	pH 6	pH 7	pH 8	pH 9
EC 2.4.2.1 Purine-nucleoside phosphorylase					
Xanthine+ribose 1-phos=xanthosine+Pi	2.3×10^3	1.7×10^3	8.7×10^2	6.6×10^2	6.3×10^2
EC 2.7.4.10 Nucleoside-triphosphate-adenylate kinase					
XTP+AMP=XDP+ADP	2.6	2.5	3.1	4.0	4.2
EC 3.2.2.1 Purine nucleosidase					
Xanthosine+H_2O=xanthine+ribose	16.3	16.4	17.2	18.3	18.6
EC 3.5.4.3 Guanine deaminase					
Guanine+H_2O=xanthine+ammonia	8.9×10^4	9.4×10^3	1.5×10^3	7.2×10^2	4.8×10^2
EC 3.5.4.15 Guanosine deaminase					
Guanosine+H_2O=xanthosine+ammonia	8.9×10^4	9.4×10^3	1.5×10^3	6.5×10^2	4.5×10^2
EC 6.3.5.2 GMP synthase (glutamine-hydrolyzing)					
ATP+XMP+glutamine+H_2O=AMP+pyrophosphate+GMP+L-glutamate	1.9×10^4	4.9×10^5	3.1×10^7	1.1×10^9	9.0×10^{10}
EC 6.3.4.1 GMP synthase					
ATP+XMP+ammonia=AMP+pyrophosphate+GMP	95	2.4×10^3	1.5×10^5	5.4×10^6	2.8×10^8

of reactions for which apparent equilibrium constants cannot currently be calculated:

$$\text{EC1.7.1.7 GMP reductase : GMP} + \text{NADP}_{red} = \text{NADP}_{ox} + \text{ammonia} + \text{IMP} \quad (17)$$

$$\text{EC1.1.1.205 IMP dehydrogenase : IMP} + \text{NAD}_{ox} + \text{H}_2\text{O} = \text{NAD}_{red} + \text{XMP} \quad (18)$$

The standard Gibbs energies of formation in the GTP series cannot yet be connected with the elements in their reference states. There are two ways this limitation can be removed: (1) Apparent equilibrium constants can be measured for a series of reactions connecting these species with simpler compounds for which $\Delta_f G°$ values are known with respect to the elements, or (2) the entropy of guanosine can be determined by use of the third law measurements and the enthalpy of formation is determined.

The usefulness of the species matrices given here can be increased by pointing out that when the deoxy forms of these reactants are involved in reactions the reactions have the same apparent equilibrium constants provided the deoxy form appears on both sides of the reactions. This is because the apparent equilibrium constants for the reduction of NAD to dNAD are expected to be independent of the base [13]. Calculations like those presented here can be made for the CTP, UTP, and TTP series.

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Appendix A

Table A
Apparent equilibrium constants for five deamination reactions in the ATP series at 298.15 K, I=0.25 M, and five pHs

EC number	Reaction	pH 5	pH 6	pH 7	pH 8	pH 9
3.5.4.3	Adenine+ H_2O= hypoxanthine+ ammonia	7.6×10^4	8.7×10^3	0.91×10^3	116	47.1
3.5.4.4	Adenosine+ H_2O=inosine+ ammonia	8.6×10^4	8.8×10^3	0.91×10^3	113	42.9
3.5.4.6	AMP+H_2O= IMP+ammonia	9.6×10^4	10.0×10^3	1.02×10^3	123	41.5
3.5.4.7	ADP+H_2O= IDP+ammonia	9.2×10^4	9.7×10^3	1.00×10^3	140	71.6
3.5.4.18	ATP+H_2O= ITP+ammonia	8.8×10^4	9.3×10^3	0.96×10^3	120	45.7

References

[1] R.A. Alberty, R.N. Goldberg, Calculation of thermodynamic formation properties of biochemical reactants at specified pH and pMg, Biochemistry 31 (1992) 10610–10615.
[2] J. Boerio-Goates, M.R. Francis, R.N. Goldberg, M.A.V. Ribeiro da Silva, M.D.M.C. Ribeiro da Silva, Y.B. Tewari, Thermochemistry of adenosine, J. Chem. Thermodyn. 33 (2001) 929–947.
[3] J.S. Boyer, M.R. Francis, J. Boeiro-Goates, Heat capacity measurements and thermodynamic functions of crystalline adenine; revised thermodynamic properties of aqueous adenine, J. Chem. Thermodyn. 35 (2003) 1917–1928.
[4] R. A. Alberty, BasicBiochemData3, 2005. http://library.wolfram.com/infocenter/MathSource/5704.
[5] J. Boeiro-Goates, S.D. Hopkins, R.A.R. Monteiro, M.D.M. Riberio da Silva, M.A.V. Riberio da Silva, R.N. Goldberg, Thermochemistry of inosine, J. Chem. Thermodyn. 37 (2005) 1239–1249.
[6] R.A. Alberty, Biochemical Thermodynamics: Applications of Mathematica, Wiley, Hoboken, NJ, 2006.
[7] D. Voet, J.G. Voet, Biochemistry, 3rd ed.Wiley, Hoboken, NJ, 2004.
[8] Enzyme nomenclature, http://www.chem.qmw.ac.uk/iubmb/enzyme/, http://www.ebi.ac.uk/thornton-srv/databases/enzymes/, http://us.expasy.org/enzyme/.
[9] R.M.C. Dawson, et al., Data for Biochemical Research, 3rd ed. Clarendon Press, Oxford, 1986.
[10] P.O.P. Ts'o, Basic Principles in Nucleic Acid Chemistry, Academic Press, 1974.
[11] R. Wolfenden, The free energy of hydrolysis of adenosine to inosine and ammonia, J. Biol. Chem. 242 (1967) 4711–4714.
[12] R.A. Alberty, Inverse Legendre transform in biochemical thermodynamics: applied to the last five reactions in glycolysis, J. Phys. Chem. 106 B (2002) 6594–6599.
[13] R.A. Alberty, Thermodynamic properties of nucleotide reductase reactions, Biochemistry 43 (2004) 9840–9845.

Glossary

$\Delta_f G^o$: standard Gibbs energy of formation of a species (kJ mol^{-1})
$\Delta_f H°$: standard enthalpy of formation of a species (kJ mol^{-1})
$\Delta_f G'°$: standard transformed Gibbs energy of formation of a reactant (kJ mol^{-1})
$\Delta_r G'°$: standard transformed reaction Gibbs energy of reaction (kJ mol^{-1})
K: equilibrium constant of a chemical reactions (dimensionless)
K': apparent equilibrium constant at a specified pH (dimensionless)
N_H: number of hydrogen atoms in a species (dimensionless)
$\Delta_r N_H$: change in the number of hydrogen ions bound in a reaction at a specified pH (dimensionless)
pK: $-\log K$
z: charge on an ion