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A consistent set of formation properties of nucleic acid compounds Nucleosides, nucleotides and nucleotide-phosphates in aqueous solution

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Abstract

Starting from formation properties of purines and pyrimidines, enthalpy of formation, Gibbs energy of formation, entropy of formation and heat capacity of several nucleosides, nucleotides and nucleotide-phosphates were calculated in dilute aqueous solution. For these calculations, the formation properties of ribose-1-phosphate were required and were calculated from data of various sources. Data for some enzymatic equilibrium constants were also used. To complete the set of formation properties of nucleosides and nucleotides, the energy contributions of some chemical bonds were calculated. The proposed values were reconciled with chemical and physical equilibrium data, validating the method of calculation used.

Keywords: Formation properties; Enzymatic equilibrium; Sugar-phosphate; Nucleosides; Nucleotides; Nucleotide-phosphates

1. Introduction

Nucleotides hold a key position in almost all biochemical processes, entering into the composition of nucleic acid and chemical energy carriers used in many metabolic reactions [1].

The phosphorylation properties of AMP and ADP have been extensively studied [2–8]. Further data are available for IMP/inosine, GMP/guanine and adenosine/adenine [9–14]. The proton dissociation properties of nucleosides and nucleotides have also been the subject of many studies [15–23], and their complex formation properties have been studied by several authors [24–34]. A common problem in the treatment of biochemical equilibria is the observed dependency of equilibrium constants, enthalpies of reaction and the stoichiometry of the reaction itself upon variables such as pH, temperature, metal–ion concentration and ionic strength. The underlying cause of these variations is the multiplicity of ionic and metal-bound species of the molecules participating in the reaction, and the presence of both long-range electrostatic and short-range interactions among the various solute species. Any systematic processing of such data requires a mathematical treatment that includes the combined effects of these variables, and that can determine the values of thermodynamic properties of studied species under a wide range of experimental conditions. Such a treatment was developed by Ould-Moulaye and co-workers [37,41] for purines and pyrimidines.

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Nomenclature

$\overline{C}^{\circ}_{p}\mathrm{aq},i$	standard heat capacity of 1 mol of species *i* in aqueous solution (J mol^{-1} K^{-1})
$\overline{C}'^{\circ}_{p}\mathrm{aq},i$	transformed heat capacity of reactant *i* (sum of species) in aqueous solution in physiological conditions (J mol^{-1} K^{-1})
$\Delta_{\mathrm{r}}\overline{C}^{\circ}_{p}$	heat capacity change in reaction in standard conditions (J mol^{-1} K^{-1})
$\Delta_{\mathrm{r}}\overline{C}'^{\circ}_{p}$	heat capacity change in reaction in physiological conditions (J mol^{-1} K^{-1})
$\Delta_{\mathrm{f}}G^{\circ}_{i}(T_{\mathrm{r}};\mathrm{aq})$	standard Gibbs energy of formation or standard chemical potential of formation of 1 mol of species *i* in the ideal solution of *i* in water (kJ mol^{-1})
$\Delta_{\mathrm{f}}G_{i}(T;m_i;\mathrm{aq})$	Gibbs energy of formation of species *i* in aqueous solution of molality m_i (kJ mol^{-1})
$\Delta_{\mathrm{f}}G'^{\circ}_{i}(T_{\mathrm{r}};\mathrm{aq})$	transformed Gibbs energy of formation of 1 mol of reactant *i* at 298.15 K, pH = 7, and $I_{\mathrm{m}} = 0.1$ M (kJ mol^{-1})
$\Delta_{\mathrm{f}}G'_{i}(T;m_i;\mathrm{aq})$	transformed Gibbs energy of formation of 1 mol of reactant *i* at given *T*, pH, and I_{m} (kJ mol^{-1})
$\Delta_{\mathrm{r}}G'(T;\ \mathrm{aq})$	Gibbs energy change for reaction in aqueous solution, unit total molality for each reactant (kJ mol^{-1})
$\Delta_{\mathrm{r}}G^{\circ}(T_{\mathrm{r}};\ \mathrm{aq})$	standard Gibbs energy change for reaction in the ideal aqueous solution at 298.15 K and $I_{\mathrm{m}} = 0.1$ M, unit molality for each species (kJ mol^{-1})
$\Delta_{\mathrm{r}}G'^{\circ}(T_{\mathrm{r}};\mathrm{aq})$	Gibbs energy change for reaction in aqueous solution at 298.15 K, pH = 7, and $I_{\mathrm{m}} = 0.1$ M, unit total molality for each reactant (kJ mol^{-1})
$\Delta_{\mathrm{f}}H^{\circ}_{i}(T_{\mathrm{r}};\mathrm{aq})$	standard enthalpy of formation of 1 mol of species *i* in the ideal solution of *i* in water (kJ mol^{-1})
$\Delta_{\mathrm{f}}H_{i}(T;m_i;\mathrm{aq})$	enthalpy of formation of species *i* in aqueous solution of molality m_i (kJ mol^{-1})
$\Delta_{\mathrm{f}}H'^{\circ}_{i}(T_{\mathrm{r}};\mathrm{aq})$	transformed enthalpy of formation of 1 mol of reactant *i* at 298.15 K, pH = 7, and $I_{\mathrm{m}} = 0.1$ M (kJ mol^{-1})
$\Delta_{\mathrm{f}}H'_{i}(T;m_i;\mathrm{aq})$	transformed enthalpy of formation of 1 mol of reactant *i* at given *T*, *P*, pH, and I_{m} (kJ mol^{-1})
$\Delta_{\mathrm{r}}H'(T;\ \mathrm{aq})$	enthalpy change for reaction in aqueous solution; unit total molality for each reactant (kJ mol^{-1})
$\Delta_{\mathrm{r}}H^{\circ}(T_{\mathrm{r}};\ \mathrm{aq})$	standard enthalpy change for reaction in the ideal aqueous solution at 298.15 K and $I_{\mathrm{m}} = 0.1$ M, unit molality for each species (kJ mol^{-1})
$\Delta_{\mathrm{r}}H'^{\circ}(T_{\mathrm{r}};\mathrm{aq})$	enthalpy change for reaction in aqueous solution at 298.15 K, pH = 7, and $I_{\mathrm{m}} = 0.1$ M, unit total molality for each reactant (kJ mol^{-1})
I_{m}	ionic strength calculated with ionic concentration in mol l^{-1} (M)
K_{c}	equilibrium constant of complex formation
K'	apparent equilibrium constant
m_i	molality of species *i* (mol kg^{-1})
$S^{\circ}_{i}(T;\mathrm{aq})$	absolute entropy of compound *i* at temperature *T* in an ideal aqueous solution of molality 1 mol kg^{-1} (J mol^{-1} K^{-1})
$\Delta_{\mathrm{f}}S^{\circ}_{i}(T_{\mathrm{r}};\mathrm{aq})$	standard entropy of formation of 1 mol of species *i* in the ideal solution of *i* in water (J mol^{-1} K^{-1})
$\Delta_{\mathrm{f}}S_{i}(T;m_i;\mathrm{aq})$	entropy of formation of 1 mol of species *i* in aqueous solution of molality m_i (J mol^{-1} K^{-1})
$\Delta_{\mathrm{f}}S'^{\circ}_{i}(T_{\mathrm{r}};\mathrm{aq})$	transformed entropy of formation of 1 mol of reactant *i* at 298.15 K, pH = 7, and $I_{\mathrm{m}} = 0.1$ M (kJ mol^{-1} K^{-1})
$\Delta_{\mathrm{r}}S^{\circ}(T_{\mathrm{r}};\ \mathrm{aq})$	standard entropy change for reaction in the ideal aqueous solution at 298.15 K and $I_{\mathrm{m}} = 0.1$ M, unit molality for each species (kJ mol^{-1} K^{-1})

$\Delta_r S'^\circ(T_r;\mathrm{aq})$	entropy change for reaction in aqueous solution at 298.15 K, pH = 7, and $I_m = 0.1$ M, unit total molality for each reactant (kJ mol^{-1})
T	temperature (K)
T_r	reference temperature $T_r = 298.15$ (K)
Subscripts	
c	reaction of complex formation
f	formation
hydr	reaction of hydrolysis
p	reaction of proton dissociation of an acid

In this work, we used the values of formation properties of purines and pyrimidines bases to compile consistent data for the enthalpy of formation, Gibbs energy of formation, entropy and heat capacity of nucleosides, nucleotides and nucleotide-phosphates in a common standard state and under a range of conditions. As acid dissociation constants and complex ion dissociation constants are necessary, these data were included together with published data for enzymatic equilibria constants, values of enthalpy and Gibbs energy of formation, and combustion energies.

When necessary, we used prediction methods to fill gaps. These methods are primarily based on structural considerations and assumptions concerning bonds energies. The thermodynamic consistency of these calculations was checked by comparing the computed predictions of equilibrium constants of some enzyme-catalyzed reactions at fixed pH, metal ion concentration and ionic strength with available data.

2. Standard and reference states and notations

To guarantee the thermodynamic consistency, all formation properties are calculated using the standard formation properties of the elements as reference [41,42]. The standard state used for single species (neutral or charged species) is the ideal aqueous solution of unit molality at 298.15 K. The formation properties in this standard state are noted $\Delta_f H_i^\circ, \Delta_f G_i^\circ, \Delta_f S_i^\circ, \overline{C}_p^\circ \mathrm{aq},i$. The corresponding reaction properties between single species are noted $\Delta_r H^\circ, \Delta_r G^\circ, \Delta_r S^\circ, \Delta_r \overline{C}_p^\circ$.

Knowing that many components are dissociated and/or complexed in aqueous solution, it is necessary to calculate global formation properties accounting for the different forms in solution at specified pH, ionic strength and complexing ions molalities. The formation properties of 1 mol of this so-called pseudo-isomer or reactant at specified values of pH, I_m and complexing ions molalities are noted $\Delta_f H'_i, \Delta_f G'_i, \Delta_f S'_i, \overline{C}'_p$, where the subscript i denotes for the global form of the reactant like ATP, Pi, etc. The corresponding reaction properties at specified pH, I_m and ions molalities are noted $\Delta_r H', \Delta_r G', \Delta_r S', \Delta_r \overline{C}'_p$. In order to make these calculations directly usable for biochemical applications, a "physiological" standard state is also used corresponding to a commonly accepted reference situation for biological media: $T_r = 298.15$ K, pH = 7, $I_m = 0.1$ M, pMg = 3 (pMg $= -\log_{10}(\gamma_{\mathrm{Mg}^{2+}} m_{\mathrm{Mg}^{2+}})$), unit molality of reactant. The formation properties of 1 mol of pseudo-isomer or reactant i in this state is noted $\Delta_f H'^\circ_i, \Delta_f G'^\circ_i, \Delta_f S'^\circ_i, \overline{C}'_p{}^\circ$. The reaction properties are noted $\Delta_r H'^\circ, \Delta_r G'^\circ, \Delta_r S'^\circ, \Delta_r \overline{C}'_p{}^\circ$. They correspond to the values of the reaction properties found in most biochemistry textbooks.

3. Calculation of the formation properties of nucleosides

Nucleosides are formed from a purine or pyrimidine base by addition of a ribose on N9 in purines or N1 in pyrimidines by the reaction:

$$\text{ribose} + \text{purine or pyrimidine} \rightarrow \text{nucleoside} + H_2O \tag{1}$$

Nucleotides are formed from nucleosides by addition of one or several phosphate groups:

$$\text{nucleoside} + \text{Pi} \rightarrow \text{nucleotide} + H_2O \tag{2}$$

Examples of nucleosides and nucleotides are presented in Table 1.

3.1. Assumptions and principles of calculation

Unlike the purines and pyrimidines [41], no data concerning the nucleosides and nucleotides in the

Table 1
Examples of nucleotides in the purine and pyrimidine groups

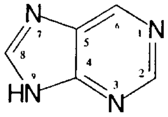
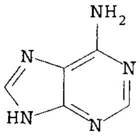
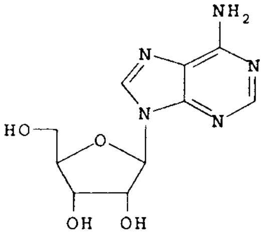
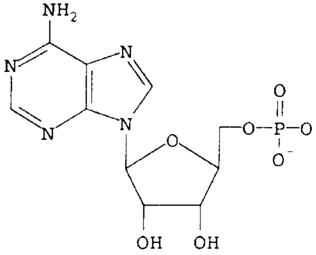
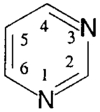
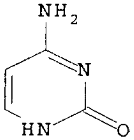
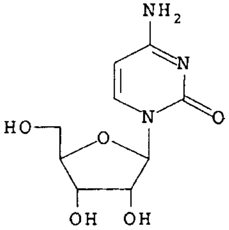
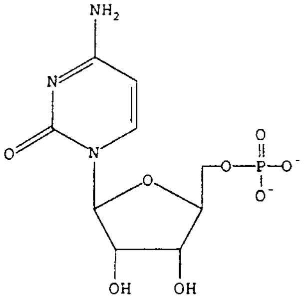
Group	Base	Nucleosides	Nucleotides
 Purine	 Adenine	 Adenosine	 Adenosine monophosphate (AMP^{2-})
 Pyrimidine	 Cytosine	 Cytidine	 Cytidine monophosphate (CMP^{2-})

Table 2
Available data for formation properties of nucleosides

Reaction	Apparent equilibrium constant	T (K)	pH	pMg	I_m (M)	Reference
Adenosine + Pi → adenine + R1P	5.4×10^{-3}	298.15	7		0.11	[9]
Guanosine + Pi → guanine + R1P	9.26×10^{-3}	311.15	7	3	0.25	[13]
Inosine + Pi → hypoxanthine + R1P	1.64×10^{-2}	311.15	7	3	0.25	[13]
Xanthosine + Pi → xanthine + R1P	1.56×10^{-2}	311.15	7	3	0.25	[13]
Inosine + thymine → 5-methyluridine + hypoxanthine	0.21	313.15	7			[10]
Inosne + thymine → 5-methyluridine + hypoxanthine	0.25	333.15	7			[10]
Thymidine + Pi → thymine + R1P	6.2×10^{-2}	313.15	7			[10]
Uridine + Pi → uracile + R1P	0.078	310.15	8.2			[10]
Uridine + Pi → uracile + R1P	0.031	310.15	7.4			[10]

solid state are available. The only published data concern enzymatic equilibria [2,3]. The measured constants are given in Table 2. They are primarily equilibrium data for the nucleoside phosphorylases in the reaction:

$$\text{nucleoside} + \text{Pi} \rightarrow \text{purine or pyrimidine} + \text{R1P} \qquad (3)$$

In reaction (3), the calculation of the formation properties of nucleosides requires knowing the formation properties for inorganic phosphate Pi, ribose-1-phosphate (R1P) and the purines or pyrimidines, in addition to the equilibrium constants, and more generally the properties associated with the reactions of type 3.

3.2. Estimation of the formation properties of inorganic phosphate Pi

Data on Pi are given in Tables 3–5. They concern the formation properties of all the forms that Pi can take in solution. The starting values concerning formation properties of phosphate are taken from [42]. The reference states for elements were carbon graphite, H_2 gas, N_2 gas, O_2 gas and P crystalline white. The values of heat capacities in aqueous solutions are taken from [43]. Calculations of these properties are possible from pK values and the constants of complex formation with Mg^{2+} ions ([41], Eqs. (24) and (25)). To illustrate the influence of pH and pMg, the dependence of the transformed Gibbs energy is plotted in Figs. 1 and 2 as a function of these two parameters.

3.3. Calculation of formation properties of ribose-1-phosphate

The formation properties of R1P were calculated (Table 6) starting from data for ribose and data for the phosphorylation of sugars [36]. The enthalpy of R1P, which is not given in the data collected by Goldberg and Tewari [36], was estimated by assuming that the reaction

$$\text{ribose} + HPO_4{}^{2-} \rightarrow R1P^{2-} + H_2O \qquad (4)$$

Table 3
Standard acid/base dissociation properties for inorganic phosphate Pi and complex formation properties with Mg^{2+} at 298.15 K
Acid/base dissociation properties

pK [21]	$\Delta_r H^\circ_p(T_r;\text{aq})$ (kJ mol^{-1})	$\Delta_r S^\circ_p(T_r;\text{aq})$ [21] (J K^{-1} mol^{-1})	$\Delta_r\overline{C}^\circ_p$p (J K^{-1} mol^{-1})
2.12	−7.86 [21]	−66.9	−128
7.20	4.14 [35]	124.0	−220
12.40	17.57 [21]	−178.5	−242
Complex formation properties with Mg^{2+}: $HPO_4{}^{2-} + Mg^{2+} \rightarrow MgHPO_4$			
pK_c	$\Delta_r H^\circ_c(T_r;\text{aq})$ (kJ mol^{-1})	$\Delta_r S^\circ_c(T_r;\text{aq})$ (J K^{-1} mol^{-1})	$\Delta_r\overline{C}^\circ_p$c (J K^{-1} mol^{-1})
2.70 [35]	−12.20 [35]	−92.6	−251 [35]

Table 4
Formation properties of inorganic phosphate Pi and calculated properties in several conditions[a,b]

Species	$\Delta_f H_i^\circ(T_r;\mathrm{aq})$ (kJ mol^{-1})	$\Delta_f G_i^\circ(T_r;\mathrm{aq})$ (kJ mol^{-1})	$\Delta_f S_i^\circ(T_r;\mathrm{aq})$ (J K^{-1} mol^{-1})	$\overline{C}_p^\circ\mathrm{aq},i$ (J K^{-1} mol^{-1})	$\Delta_f H_i(T_r;\ m_i;\ \mathrm{aq})$ (kJ mol^{-1})	$\Delta_f G_i(T_r;\ m_i;\ \mathrm{aq})$ (kJ mol^{-1})	$\Delta_f S_i(T_r;\ m_i;\ \mathrm{aq})$ (J K^{-1} mol^{-1})	m_i (mol kg^{-1})
H_3PO_4	−1295.28	−1149.30	−489.6	104	−1295.28	−1180.11	−386.3	0.0
$H_2PO_4^-$	−1303.14	−1137.20	−556.6	−24	−1302.83	−1140.15	−545.6	0.389
HPO_4^{2-}	−1299.00 [42]	−1096.10	−680.5 [42]	−244 [43]	−1297.76	−1100.19	−662.6	0.515
$MgHPO_4$	−1753.80	−1566.17	−629.3	−9	−1753.80	−1571.98	−609.8	0.096
PO_4^{3-}	−1281.43	−1025.32	−859.0	−486	−1278.64	−1060.24	−732.5	0.0
Mg^{2+}	−467.0	−454.66	−41.4	−16	−465.76	−471.78	20.20	
H^+	0.0	0.0	0.0	0.0	0.31	−39.96	135.07	

[a] Standard formation properties of all species at standard state (ideal aqueous solution of unit molality) calculated from the properties of HPO_4^{2-} given in [42,43] using the acid/base and complex formation properties of Table 3.

[b] Formation properties of all species at pH = 7, pMg = 3, $T = 298.15$ K and $I_m = 0.1$ M. Total phosphate molality $m_{\mathrm{Pi}} = 1$ mol kg^{-1}.

Table 5
Transformed properties for reactant Pi in physiological conditions: $T_r = 298.15$ K, pH = 7, pMg = 3 and $I_m = 0.1$ M[a]

$\Delta_f H'^\circ_{\mathrm{Pi}}(T_r; m_{\mathrm{Pi}} = 1; \mathrm{aq}) = -1298.3$ kJ mol^{-1}
$\Delta_f G'^\circ_{\mathrm{Pi}}(T_r; m_{\mathrm{Pi}} = 1; \mathrm{aq}) = -1180.11$ kJ mol^{-1}
$\Delta_f S'^\circ_{\mathrm{Pi}}(T_r; m_{\mathrm{Pi}} = 1; \mathrm{aq}) = -396.41$ J mol^{-1} K^{-1}
$\overline{C}'^\circ_p\mathrm{aq,Pi} = -144.30$ J mol^{-1} K^{-1}

[a] The sum of molalities of species is unity.

has the same entropy as the similar reaction with ribose-5-P^{2-}, i.e. $\Delta_r S^\circ(T_r;\mathrm{aq}) = -31.6$ J mol^{-1} K^{-1}.

According to the data of Table 6, this assumption leads to

$$\Delta_r S^\circ(T_r;\mathrm{aq}) = -31.6\,\mathrm{J\,mol^{-1}\,K^{-1}}$$

$$S^\circ_{\mathrm{R1P^{2-}}}(T_r;\mathrm{aq}) = 69\,\mathrm{J\,mol^{-1}\,K^{-1}}$$

$$\Delta_f S^\circ_{\mathrm{R1P^{2-}}}(T_r;\mathrm{aq}) = -1539\,\mathrm{J\,mol^{-1}\,K^{-1}}$$

$$\Delta_f H^\circ_{\mathrm{R1P^{2-}}}(T_r;\mathrm{aq}) = -2034.6\,\mathrm{kJ\,mol^{-1}}$$

$$\Delta_f G^\circ_{\mathrm{R1P^{2-}}}(T_r;\mathrm{aq}) = -1575.7\,\mathrm{kJ\,mol^{-1}}$$

The heat capacity of R1P was assumed to be equal to that of ribose-5-phosphate:

$$\overline{C}_p^\circ\mathrm{aq,R1P^{2-}} = 10\,\mathrm{J\,mol^{-1}\,K^{-1}}$$

3.4. *Calculation of the formation properties of nucleosides*

The equilibrium properties given in Table 2 make it possible to calculate the formation properties of nucleosides knowing the p*K* values given in Table 7, the formation properties of purines and pyrimidines [41] and the formation properties of inorganic phosphate (Table 4). The results of calculations yielding

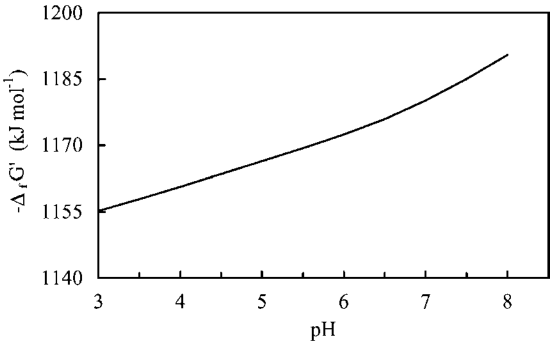


Fig. 1. Dependence of the transformed Gibbs energy of Pi, $\Delta_f G'_{\mathrm{Pi}}(T; m_{\mathrm{Pi}} = 1; \mathrm{aq})$, as a function of pH for pMg = 3.

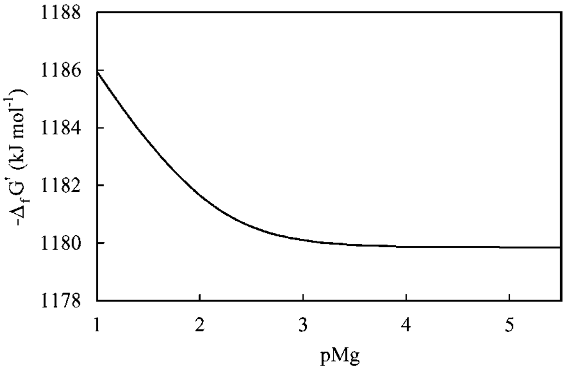


Fig. 2. Dependence of the transformed Gibbs energy of Pi, $\Delta_f G'_{\mathrm{Pi}}(T; m_{\mathrm{Pi}} = 1; \mathrm{aq})$, as a function of pMg at pH = 7.

Table 6
Standard enthalpy and Gibbs energy of phosphorylation of a sugar in the reaction: sugar + HPO_4^{2-} → sugar – phosphate^{2-} + H_2O from the compilation of Goldberg and Tewari [36][a]

Compound	Type	Reaction	$\Delta_r H^\circ(T_r;\ aq)$ (kJ mol^{-1})	$\Delta_r G^\circ(T_r;\ aq)$ (kJ mol^{-1})
Ribose	Aldose	$R/R5P^{2-}$	5.7	15.1
Arabinose	Aldose	$Ar/Ar5P^{2-}$		16.0
Ribulose	Ketose	$Rub/Rub5P^{2-}$	12.4	13.5
Xylulose	Ketose	$Xyl/Xyl5P^{2-}$		22.4
Glucose	Aldose	$G/G6P^{2-}$	10.8	10.9
Mannose	Aldose	$M/M6P^{2-}$	−1.4	9.1
Galactose	Aldose	$Gal/Gal6P^{2-}$		11.2
Fructose	Ketose	$F/F6P^{2-}$	7.9	13.6
Ribose	Aldose	$R/R1P^{2-}$		22.0
Glucose	Aldose	$G/G1P^{2-}$		17.9
Galactose	Aldose	$Gal/Gal1P^{2-}$		13.8
Fructose	Ketose	$F/F1P^{2-}$		10.2

[a] $\Delta_f G^\circ_{H_2O} = -237.19\,\text{kJ mol}^{-1}$ and $\Delta_f H^\circ_{H_2O} = -283.85\,\text{kJ mol}^{-1}$ [42]: $T_r = 298.15$ K, $I_m = 0.1$ M, unit molality of each species.

the formation properties of nucleosides are given in Table 8.

The enthalpies of formation of nucleosides were estimated starting from the Gibbs energies and the entropy of formation and assuming that the reaction of hydrolysis:

$$\text{nucleoside} + H_2O \rightarrow \text{purine or pyrimidine} + \text{ribose} \quad (5)$$

had a constant entropy whichever the base considered. An average value for hydrolysis reactions was retained, i.e. $\Delta_r S'^\circ_{\text{hydr}}(T_r; \text{aq}) = 20\,\text{J mol}^{-1}\,\text{K}^{-1}$. Heat capacities were calculated taking the variation of heat capacity in the above reaction equal to the variation of entropy $\Delta_r \overline{C}'^\circ_p = 20$ J mol^{-1} K^{-1}. The results obtained are reported in Table 8. Changes of formation properties related to the reaction of the hydrolysis were calculated. The calculation of Gibbs energy of the hydrolysis reaction indicates that the Gibbs energy contribution in physiological conditions of the N–C_6 bonds ranges from −10.1 (adenosine) to −21.3 kJ mol^{-1} (uridine).

Table 7
The pK, $\Delta_r H^\circ_p(T_r; \text{aq})$, $\Delta_r S^\circ_p(T_r; \text{aq})$ and $\Delta_r \overline{C}^\circ_p$p values for proton ionization from several nucleosides at 298.15 K and for $I_m = 0.1$ M in sites indicated in Table 1[a]

Compound	Ionization site	Reaction	pK	$\Delta_r H^\circ_p$	$\Delta_r S^\circ_p$	$\Delta_r \overline{C}^\circ_p$p[b]
Adenosine	N_1H^+	$H_2A^+ \Leftrightarrow HA + H^+$	3.52 [15]	13.0 [15]	−24	−43
Adenosine	Ribose OH	$HA \Leftrightarrow A^- + H^+$	12.35 [19]	40.6 [19]	−100	−180
Guanosine	N_7H^+	$H_3G^+ \Leftrightarrow H_2G + H^+$	1.9 [16]	13.4 [16]	8	15
Guanosine	N_1H–C_6O	$H_2G \Leftrightarrow HG^- + H^+$	9.25 [16]	32.0 [16]	−70	−126
Guanosine	Ribose OH	$HG^- \Leftrightarrow G^{2-} + H^+$	12.33 [16]	45.40 [16]	−84	−151
Inosine	N_1H–C_6O	$H_2I \Leftrightarrow HI^- + H^+$	8.96 [16]	27.2 [16]	−80	−144
Inosine	Ribose OH	$HI^- \Leftrightarrow I^{2-} + H^+$	12.4 [16]	44.6 [16]	−87	−157
Xanthosine	N_1H–C_6O	$H_2X \Leftrightarrow HX^- + H^+$	5.7 [16]	15.6 [16]	−56	−101
Xanthosine	Ribose OH	$HX^- \Leftrightarrow X^{2-} + H^+$	12.0 [16]	45.4 [16]	−77	−139
Cytidine	N_1H^+	$H_2C^+ \Leftrightarrow HC + H^+$	4.08 [18]	21.4 [18]	−12	−67 [18]
Cytidine	Ribose OH	$HC \Leftrightarrow C^- + H^+$	12.50 [18]	43.1 [18]	−95	−171
Thymidine	N_1H–C_6O	$H_2T \Leftrightarrow HT^- + H^+$	9.79 [18]	30.6 [18]	−85	−125.5 [18]
Uridine	N_1H–C_6O	$H_2U \Leftrightarrow HU^- + H^+$	9.30 [18]	30.3 [18]	−76	−121.3 [18]
Uridine	Ribose OH	$HU^- \Leftrightarrow U^{2-} + H^+$	12.59 [18]	45.6 [18]	−88	−158

[a] $\Delta_r S^\circ_p(T_r; \text{aq})$ values are calculated from $\Delta_r G^\circ_p(T_r; \text{aq})$ and $\Delta_r H^\circ_p(T_r; \text{aq})$ values. $\Delta_r H$ is in kJ mol^{-1}, $\Delta_r S$ and $\Delta_r \overline{C}_p$ are in J mol^{-1} K^{-1}. In these reactions A, G, etc. refer to adenosine, guanosine, etc.

[b] This work (Eq. (44) in [41]).

Table 8
Standard formation properties of nucleosides at 298.15 K and properties of the reaction: ncleoside + $H_2O \rightarrow$ purine (or pyrimidine) + ribose at 298.15 K, pH = 7 and $I_m = 0.1$ M[a]

Compound	$\Delta_f G_i^\circ(T_r;\mathrm{aq})$ (kJ mol^{-1})	$\Delta_f H_i^\circ(T_r;\mathrm{aq})$ (kJ mol^{-1})	$\overline{C}_p^\circ\mathrm{aq},i$ (J mol^{-1} K^{-1})	$\Delta_r G'^\circ_{\mathrm{hydr}}(T_r;\mathrm{aq})$ (kJ mol^{-1})	$\Delta_r H'^\circ_{\mathrm{hydr}}(T_r;\mathrm{aq})$ (kJ mol^{-1})
Adenosine $C_{10}H_{13}N_5O_4$	**−180.2**	*−614.5*	*400*	**−10.1**	*−4.2*
Guanosine $C_{10}H_{13}N_5O_5$	**−424.2**	*−900.2*	*365*	**−10.8**	*−4.7*
Inosine $C_{10}H_{12}N_4O_5$	**−399.2**	*−818.6*	*393*	**−12.2**	*−6.3*
Xanthosine $C_{10}H_{12}N_4O_6$	**−625.2**	*−1084.6*	*364*	**−20.4**	*−13.9*
Cytidine $C_9H_{13}N_3O_5$	*−516.8*	−927	*387*	*−21.3*	*−15.3*
Thymidine $C_{10}H_{14}N_2O_6$	**−763**	*−1176.7*	*435*	**−16.1**	−10
Uridine $C_9H_{12}N_2O_6$	**−735.9**	*−1133.2*	*356*	**−21.3**	*−15.1*

[a] Bold numbers are measured values and italics are values estimated from the assumption $\Delta_r S'^\circ_{\mathrm{hydr}}(T_r;\mathrm{aq}) = 20$ J mol^{-1} K^{-1}.

For the pyrimidines group only two constants of equilibrium were available (thymidine and uridine). We assumed that the Gibbs energy contributionof N–C_6 bonds for cytidine had the same value as for uridine ($\Delta_r G'^\circ_{\mathrm{hydr}}(T_r;\mathrm{aq}) = -21.3$ kJ mol^{-1}).

For the purine group, the Gibbs energy of the bond for adenosine, guanosine and inosine was closely similar (-11 kJ mol^{-1}). In contrast, the value obtained for xanthosine was appreciably different for no obvious apparent reason, considering the chemical structures. The experimentally determined equilibrium constant or p*K* values of xanthine and/or of xanthosine (7.53 and 5.67, respectively) (Table 7) may be inaccurate; these values are important in the determination of the transformed properties at pH = 7.

In conclusion, calculated values in Table 8 give a first estimation of the formation properties of nucleosides, which needed to be checked against properties of combustion and solubility data in aqueous solution as carried out for purines and pyrimidines [41].

To check the consistency of the proposed values some additional data were used to compare the results obtained in this work. Camici et al. [9] have measured the change of Gibbs energy of hydrolysis of adenosine: $\Delta_r G'^\circ_{\mathrm{hydr}}(T_r;\mathrm{aq}) = -9.9$ kJ mol^{-1} at pH = 7, 298.15 K and for $I_m = 0.1$ M. This result is in close agreement with the value calculated in this work, $\Delta_r G'^\circ_{\mathrm{hydr}}(T_r;\mathrm{aq}) = -10.1$ kJ mol^{-1} (Table 8). As an other example, calculated and measured values [12,38] of the apparent equilibrium constants in reactions (6) and (7):

$$\text{adenosine} + H_2O \rightarrow \text{inosine} + NH_3 \qquad (6)$$

and

$$\text{cytidine} + H_2O \rightarrow \text{uridine} + NH_3 \qquad (7)$$

are shown in Figs. 3 and 4.

As these results are entirely predictive, we consider that the agreement with literature data is very satisfactory given that these results were not used in the estimation of the formation properties.

In addition, Larson et al. [11] estimated the enthalpy of the reaction (6) at -49.4 ± 0.7 kJ mol^{-1}, which is in close agreement with our calculations, which give a value of -50.9 kJ mol^{-1}. These comparisons validate the results in Table 8.

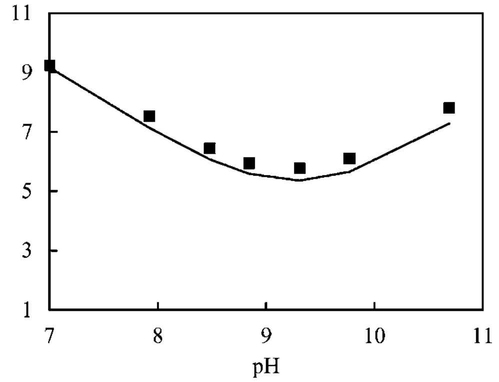


Fig. 3. Apparent equilibrium constant $K' = m_{\mathrm{inosine}} m_{NH_3} / m_{\mathrm{adenosine}}$ (mol kg^{-1}) for the reaction adenosine + $H_2O \Leftrightarrow$ inosine + NH_3 as a function of pH. Comparison between experimental data [12] and values calculated in this work. Standard formation properties of $NH_4{}^+$ are $\Delta_f G^\circ_{NH_4^+}(T_r;\mathrm{aq}) = -79.46$ kJ mol^{-1} and $\Delta_f H^\circ_{NH_4^+}(T_r;\mathrm{aq}) = -133.26$ kJ mol^{-1} [42] and of NH_3 are $\Delta_f G^\circ_{NH_3}(T_r;\mathrm{aq}) = -26.67$ kJ mol^{-1} and $\Delta_f H^\circ_{NH_3}(T_r;\mathrm{aq}) = -80.92$ kJ mol^{-1} [21].

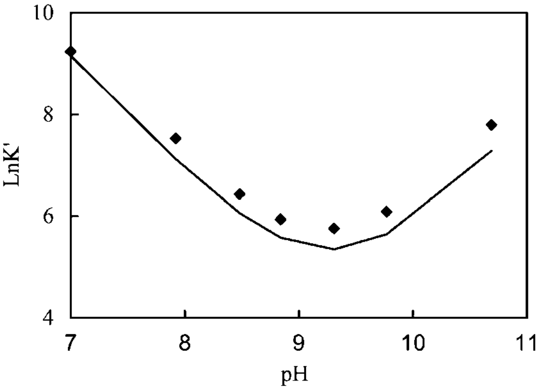


Fig. 4. Apparent equilibrium constant $K' = m_{\text{uridine}} m_{NH_3}/m_{\text{cytidine}}$ (mol kg^{-1}) for the reaction cytidine + H_2O ⇔ uridine + NH_3 as a function of pH. Comparison between experimental data [38] and values calculated in this work. Standard formation properties of NH_4^+ are $\Delta_f G^{\circ}_{NH_4^+}(T_r; \text{aq}) = -79.46\,\text{kJ mol}^{-1}$ and $\Delta_f H^{\circ}_{NH_4^+}(T_r; \text{aq}) = -133.26\,\text{kJ mol}^{-1}$ [42] and of NH_3 are $\Delta_f G^{\circ}_{NH_3}(T_r; \text{aq}) = -26.67$ kJ mol^{-1} and $\Delta_f H^{\circ}_{NH_3}(T_r; \text{aq}) = -80.92\,\text{kJ mol}^{-1}$ [21].

4. Calculation of the formation properties of nucleotides

For nucleotides, complex formation properties must also be taken into account. Unlike purines and pyrimidines, the nucleotides often occur as complexes, the stability of which has to be studied [30–34]. A more recent study [29] afforded a full set of data on complex formation in biological media. However, the properties of complexation with ions Na^+ and K^+ have been studied only for the series AMP, ADP, ATP as indicated in [29] and had to be computed for the other nucleotides.

4.1. Formation properties of nucleotides monophosphates

To calculate the formation properties of nucleotides phosphates, p*K* values (Tables 7 and 9) and values of complexation constants (Table 10) were needed. As indicated in Table 1, the nucleotides are formed from nucleosides by reaction (1).

The bond with the phosphate group is formed in position 5 of the ribosyl radical. From the results in Table 6, the values of $\Delta_r G^{\circ}(T_r; \text{aq})$ and $\Delta_r S^{\circ}(T_r; \text{aq})$ for nucleotide formation from nucleoside and inorganic phosphate (reaction (1)) might be expected to be the same as for the reactions with ribose/ribose 5P or arabinose/arabinose 5P, which gives representative values for the bond energies between the phosphate group and aldose in position C_5. This gave $\Delta_r G'^{\circ}(T_r; \text{aq}) = 15\,\text{kJ mol}^{-1}$ and $\Delta_r S'^{\circ}(T_r; \text{aq}) = -30\,\text{J mol}^{-1}\,\text{K}^{-1}$ for this bond. The available data [11,24] for the adenosine/AMP reaction gave $\Delta_r G'^{\circ}(T_r; \text{aq}) = 13\,\text{kJ mol}^{-1}$ and $\Delta_r S'^{\circ}(T_r; \text{aq}) = -49\,\text{J mol}^{-1}\,\text{K}^{-1}$. This is in close agreement with the bond energies previously estimated from ribose/ribose 5P formation properties. The formation properties of AMP^{2-} were calculated accordingly, giving

$$\Delta_f G^{\circ}_{\text{AMP}^{2-}}(T_r; \text{aq}) = -1026.1\,\text{kJ mol}^{-1}$$

$$\Delta_f H^{\circ}_{\text{AMP}^{2-}}(T_r; \text{aq}) = -1629.3\,\text{kJ mol}^{-1}$$

$$\overline{C}^{\circ}_{p}\text{aq, AMP}^{2-} = -103\,\text{J mol}^{-1}\,\text{K}^{-1}$$

The formation properties of IMP^{2-} and GMP^{2-} were calculated in the same way. The calculated and the available experimental values are compared in Table 11.

For pyrimidine-monophosphates (CMP, UMP, TMP), no direct measurement was available. The formation properties of these compounds were estimated by considering that $\Delta_r G'^{\circ}(T_r; \text{aq})$, $\Delta_r H'^{\circ}(T_r; \text{aq})$, and $\Delta_r \overline{C}'^{\circ}_p$ for hydrolysis were equal to those for purine-monophosphates (AMP, GMP, IMP): $\Delta_r G'^{\circ}(T_r; \text{aq}) = 14$, $\Delta_r H'^{\circ}(T_r; \text{aq}) = 0\,\text{kJ mol}^{-1}$ and $\Delta_r \overline{C}'^{\circ}_p = 40$ J mol^{-1} K^{-1}. The formation properties of the bivalent ions of nucleotide monophosphate are given in Table 12.

4.2. Formation properties of nucleotides di- and triphosphates

The compared formation properties of nucleotide mono-, di- and triphosphates have been extensively studied [2,3,6,9,11,39,40] because of the importance of these compounds in cellular metabolism. Recent results published for the AMP, ADP, and ATP series [11,24] were taken as reference, making it possible to calculate the properties of species ADP and ATP starting from the results obtained for the formation properties of adenosine, and not from an arbitrary reference as generally done up to now. The results are given in Table 13.

For the reaction

$$\text{ATP} + H_2O \rightarrow \text{ADP} + \text{Pi} \qquad (8)$$

Table 9
The pK, $\Delta_r H_p^\circ(T_r;\mathrm{aq})$, $\Delta_r S_p^\circ(T_r;\mathrm{aq})$ and $\Delta_r \overline{C}_p^\circ\mathrm{p}$ values for proton ionization of several nucleotides at 298.15 K and for $I_m = 0.1$ M in indicated reactions[a]

Compound	Reaction	pK	$\Delta_r H_p^\circ(T_r;\mathrm{aq})$ (kJ mol^{-1})	$\Delta_r S_p^\circ(T_r;\mathrm{aq})$ (J mol^{-1} K^{-1})	$\Delta_r \overline{C}_p^\circ\mathrm{p}$ (J mol^{-1} K^{-1})
AMP	$H_2AMP \Leftrightarrow HAMP^- + H^+$	3.99 [20]	18.0 [20]	−16.02	−63 [20]
AMP	$HAMP^- \Leftrightarrow AMP^{2-} + H^+$	6.74 [20]	−5.4 [20]	−147.15	−126 [20]
ADP	$H_2ADP^- \Leftrightarrow HADP^{2-} + H^+$	4.37 [20]	17.6 [20]	−24.63	−63 [20]
ADP	$HADP^{2-} \Leftrightarrow ADP^{3-} + H^+$	7.20 [20]	−5.6 [20]	−156.62	−126 [20]
ATP	$H_2ATP^{2-} \Leftrightarrow HATP^{3-} + H^+$	4.70 [20]	14.9 [20]	−40.01	−63 [20]
ATP	$HATP^{3-} \Leftrightarrow ATP^{4-} + H^+$	7.62 [20]	−6.3 [20]	−167.01	−126 [20]
GMP	$H_3GMP \Leftrightarrow H_2GMP^- + H^+$	3.1 [17][b]	−0.1	−60	
GMP	$H_2GMP^- \Leftrightarrow HGMP^{2-} + H^+$	6.66 [22]	−6.1 [22]	−147.86	
GMP	$HGMP^{2-} \Leftrightarrow GMP^{3-} + H^+$	10.1 [21][b]	32.0 [21][b]	−86.0	
GDP	$H_3GDP \Leftrightarrow H_2DMP^- + H^+$	3.11 [17][b]			
GDP	$H_2GDP^- \Leftrightarrow HGDP^{2-} + H^+$	7.19 [22]	−6.2 [22]	−158.41	
GDP	$HGDP^{2-} \Leftrightarrow GDP^{3-} + H^+$	10.4 [22]	30.0 [20]	−98	
GTP	$H_3GTP^{2-} \Leftrightarrow H_2GTP^{3-} + H^+$	3.56 [23][b]	5.2 [23][b]	−50.55	
GTP	$H_2GTP^{3-} \Leftrightarrow HGTP^{4-} + H^+$	7.39 [23][b]	−6.2 [23][b]	−162.41	
GTP	$HGTP^{4-} \Leftrightarrow GTP^{5-} + H^+$	10.63 [23][b]	27.4 [23][b]	−111.48	
IMP	$H_2IMP^- \Leftrightarrow HIMP^{2-} + H^+$	6.66 [22]	−5.98 [22]	−147.56	−126 [17]
IMP	$HIMP^{2-} \Leftrightarrow IMP^{3-} + H^+$	9.62 [17]	26.0 [17]	−96.97	−200 [17]
IDP	$H_3IDP \Leftrightarrow H_2IDP^- + H^+$	4.36 [17][b]			
IDP	$H_2IDP^- \Leftrightarrow HIDP^{2-} + H^+$	7.18 [22]	−5.61 [22]	−156.28	
IDP	$HIDP^{2-} \Leftrightarrow IDP^{3-} + H^+$	9.85 [21]			
ITP	$H_3ITP^{2-} \Leftrightarrow H_2ITP^{3-} + H^+$	2.78 [23][b]	−6.52 [23][b]	−75.09	
ITP	$H_2ITP^{3-} \Leftrightarrow HITP^{4-} + H^+$	7.35 [23][b]	−6.37 [23][b]	−162.08	
ITP	$HITP^{4-} \Leftrightarrow ITP^{5-} + H^+$	10.14 [23][b]	24.64 [23][b]	−111.49	
TMP	$H_3TMP \Leftrightarrow H_2TMP^- + H^+$	1.6 [17]	−9.7[c]	−60	
TMP	$H_3TMP^- \Leftrightarrow HTMP^{2-} + H^+$	6.5 [17]	−5.5[c]	−143	
TMP	$HTMP^{2-} \Leftrightarrow TMP^{3-} + H^+$	10.4[c]	30.0[c]	−98	
CMP	$HCMP^- \Leftrightarrow CMP^{2-} + H^+$	6.62 [17][b]	−5.65 [17][b]	−145.69	
CDP	$H_2CDP^- \Leftrightarrow HCDP^{2-} + H^+$	4.82 [22]			
CDP	$HCDP^{2-} \Leftrightarrow CDP^{3-} + H^+$	7.18 [17][b]	−5.61 [17][b]	−156.28	
CTP	$H_2CTP^{2-} \Leftrightarrow HCTP^{3-} + H^+$	5.17 [23][b]	21.82 [23][b]	−25.78	
CTP	$HCTP^{3-} \Leftrightarrow CTP^{4-} + H^+$	7.65 [22]	−7.32 [22]	−171.01	
UMP	$H_2UMP^- \Leftrightarrow HUMP^{2-} + H^+$	6.63 [17][b]	−4.67 [17][b]	−142.59	
UMP	$HUMP^{2-} \Leftrightarrow UMP^{3-} + H^+$	10.19[c]	30.3[c]	−93.5	
UDP	$HUDP^{2-} \Leftrightarrow UDP^{3-} + H^+$	7.16 [17][b]	−4.52 [17][b]	−152.24	
UTP	$HUTP^{3-} \Leftrightarrow UTP^{4-} + H^+$	7.58 [22]	−8.45 [22]	−173.46	

[a] $\Delta_r S$ values are calculated from $\Delta_r G$ and $\Delta_r H$ values.

[b] Extrapolated values to $I_m = 0.1$ from indicated references.

[c] Values estimated in this work.

Table 10
The pK_c, $\Delta_r H_c^\circ(T_r; aq)$, $\Delta_r S_c^\circ(T_r; aq)$ for the reaction of complex formation at 298.15 K: $M^{n+} + L^{z-} \Leftrightarrow ML^{(n-z)}$ given by Smith et al. [29][a]

Compound	Equilibrium	pK_c	$\Delta_r H_c^\circ(T_r; aq)$ (kJ mol^{-1})	$\Delta_r S_c^\circ(T_r; aq)$ (J mol^{-1} K^{-1})
Mg^{2+}				
ATP[a]	ML/M.L	6.18	−22.9	−195.12
	MHL/M.HL	3.63	−16.9	−126.18
	M_2L/M.ML	2.69	−10.8	−87.72
GTP	ML/M.L	6.22	−23.0	−196.22
	MHL/M.HL	3.6		
ITP	ML/M.L	6.19	−23.8	−198.33
	MHL/M.HL	3.63		
CTP	ML/M.L	6.16		
	MHL/M.HL	3.5		
	M_2L/M.ML	2.65		
TTP	ML/M.L	6.22		
ADP[a]	ML/M.L	4.65	−19.0	−152.75
	MHL/M.HL	2.5	−12.5	−89.79
CDP	ML/M.L	4.43		
	MHL/M.HL	2.05		
	M_2L/M.ML	1.00		
GDP	ML/M.L		−18.0	
UDP	ML/M.L	4.64	−17.12	−146.25
AMP[a]	ML/M.L	2.79	−11.3	−91.31
GMP	ML/M.L	2.85	−9.6	−86.76
CMP	ML/M.L	2.79		
CMP	ML/M.L	2.79		
UMP	ML/M.L	3.23	−11.23	−99.50
TMP	ML/M.L	3.25		
Ca^{2+}				
ATP	ML/M.L	5.96	−19.16	−178.37
	MHL/M.HL	3.45	−11.62	−105.02
GTP	ML/M.L	5.86		
ITP	ML/M.L	5.86		
CTP	ML/M.L	5.85		
	MHL/M.HL	3.46		
TTP	ML/M.L	5.88		
ADP	ML/M.L	4.37		
	MHL/M.HL	2.51	−8.78	−77.50
GDP	ML/M.L		−18.0	
AMP-5	ML/M.L	2.78	−6.7	−75.69
CMP-5	ML/M.L	2.72		
UMP-5	ML/M.L	3.19		
TMP-5	ML/M.L	2.72		
Na^{+}				
AMP	ML/M.L	1.31		
ADP	ML/M.L	1.76		
ATP	ML/M.L	2.17	−1.68	−47.18
K^{+}				
AMP	ML/M.L	1.13		
ADP	ML/M.L	1.56		
ATP	ML/M.L	2.03	−3.61	−50.97

[a] Values given by Alberty and Goldberg [24].

at $pH = 7$, $pMg = 3$, $T = 298.15$ K and $I_m = 0.25$ M, we obtained

$$\Delta_r G'(T_r; m_{ATP} = m_{ADP} = m_{Pi} = 1; aq) = -32.5\,\text{kJ mol}^{-1}$$

$$\Delta_r H'(T_r; m_{ATP} = m_{ADP} = m_{Pi} = 1; aq) = -30.8\,\text{kJ mol}^{-1}$$

For the reaction

$$2ADP \rightarrow ATP + AMP \tag{9}$$

at $pH = 7$, $pMg = 3$, $T = 298.15$ K and $I_m = 0.25$ M, we obtained

$$\Delta_r G'(T_r; m_{ATP} = m_{ADP} = m_{AMP} = 1; aq) = 1.4\,\text{kJ mol}^{-1}$$

$$\Delta_r H'(T_r; m_{ATP} = m_{ADP} = m_{AMP} = 1; aq) = -1.7\,\text{kJ mol}^{-1}$$

Importantly, the results obtained also make it possible to calculate the properties of the preceding reactions under other conditions of pH, ionic strength and temperature.

For GMP, GDP, GTP series, data concerning the measurement of the bond enthalpy of mono–diphosphate (22.8 kJ mol^{-1}) and di–triphosphate (23.6 kJ mol^{-1}) are available [38]. These values are close to the selected values for AMP, ADP, and ATP series. This justifies extrapolating the Gibbs energy of the di- and triphosphate bonds of these series to GDP and GTP.

For other nucleotide-phosphates, we had no direct information, and so the values obtained for series AMP, ADP, ATP were used to calculate the formation

Table 11
Comparison between experimental values [10] and values calculated in this work for nucleotide monophosphates at different conditions[a]

Reaction	Conditions	$\Delta_r G'$(exp)	$\Delta_r G'$(calc)	$\Delta_r H'$(exp)	$\Delta_r H'$(calc)
AMP + H_2O ⇔ adenosine + Pi	$T = 298.15$, $I_m = 0.25$ M, pH = 7, pMg = 3	−13.4	−14.1		−0.9
AMP + H_2O ⇔ adenosine + Pi	$T = 308.15$, $I_m = 0.1$ M, pH = 8, pMg = 1.62	−13.2	−13.0		1.7
AMP + H_2O ⇔ adenosine + Pi	$T = 297.45$, $I_m = 0.015$ M, pH = 3.7		−14.4	−6.5	−1.7
IMP + H_2O ⇔ inosine + Pi	$T = 298.15$, $I_m = 1.53$ M, pH = 8.85, pMg = 4.4	−12.6	−12.4		−6.6
IMP + H_2O ⇔ inosine + Pi	$T = 298.15$, $I_m = 0.083$ M, pH = 8.15, pMg = 3		−17.7	1.54	−0.1
GMP + hypoxanthine ⇔ IMP + guanine	$T = 310.15$, $I_m = 0.1$ M, pH = 7.4, pMg = 2	2.5	2.5		−1.9
GMP + H_2O ⇔ guanosine + Pi	$T = 298.15$, $I_m = 0.6$ M, pH = 9		−15.5	2.7	2.7
AMP + H_2O ⇔ IMP + NH_3	$T = 298.15$, $I_m = 0.31$ M, pH = 7.1		−21.7	−44.3	−46.3

[a] Data are in kJ mol^{-1}.

Table 12
Standard formation properties of nucleotide monophosphates at 298.15 K[a]

Compounds	$\Delta_f G_i^\circ(T_r;\text{aq})$	$\Delta_f H_i^\circ(T_r;\text{aq})$	$\overline{C}_p^\circ$aq,i	$\Delta_r G^\circ(T_r;\text{aq})$	$\Delta_r H^\circ(T_r;\text{aq})$	$\Delta_r\overline{C}_p^\circ$
AMP^{2-}	−1026.1	−1629.3	−103	13	−1.6	22
IMP^{2-}	−1245.1	−1828.8	130	13	3	56
GMP^{2-}	−1268.0	−1914.2	90	15.1	−0.8	40
CMP^{2-}	−1361.7	−1904.2	108	14	0	40
UMP^{2-}	−1580.6	−2146.4	81	14.2	0	44
TMP^{2-}	−1607.7	−2189.9	160	14	0	40

[a] The standard state is the ideal solution of unit molality. $\Delta_r G^\circ(T_r;$ aq), $\Delta_r H^\circ(T_r;$ aq) and $\Delta_r\overline{C}_p^\circ$ refer to the reaction $YMP^{2-} + H_2O \rightarrow Y + HPO_4{}^{2-}$. $\overline{C}_p$ is in J mol^{-1} K^{-1}, G and H are in kJ mol^{-1}.

properties of these compounds. The energy of binding of mono-, di- and di–triphosphate charged (2$^-$) were assumed to be unchanged. The result concerning the formation properties of nucleotide diphosphates charged (3$^-$) and nucleotide triphosphates charged (4$^-$) are reported in Table 13. For comparison, the properties of the diphosphate bond in pyrophosphate are also reported in Table 13. Using the dissociation

Table 13
Standard formation properties of nucleotide di- and triphosphates and of pyrophosphate at 298.15 K[a]

Compound	$\Delta_f G_i^\circ(T_r;\text{aq})$	$\Delta_f H_i^\circ(T_r;\text{aq})$	$\overline{C}_p^\circ$aq,i	Reaction (1)			Reaction (2)		
				$\Delta_r G^\circ$	$\Delta_r H^\circ$	$\Delta_r\overline{C}_p$	$\Delta_r G^\circ$	$\Delta_r H^\circ$	$\Delta_r\overline{C}_p^\circ$
ADP^{3-}	−1889.7	−2623.6	−310	33.8	13.5	−220			
ATP^{4-}	−2750.0	−3614.3	−703				39.7	16.9	−200
GDP^{3-}	−2131.4	−2904.2	−97	33.5	17.0	−220			
GTP^{4-}	−2991.6	−3897.1	−256				39.7	14.1	−220
IDP^{3-}	−2108.2	−2821.0	−283	33.8	15.0	−220			
ITP^{4-}	−2968.4	−3889.4	−546				39.7	15.0	−220
CDP^{3-}	−2224.6	−2896.8	−83	33.8	15.0	−220			
CTP^{4-}	−3084.8	−3889.4	−622				39.7	15.0	−220
UDP^{3-}	−2453.5	−3139.9	−116	33.8	15.0	−220			
UTP^{4-}	−3317.1	−4144.1	−417				39.7	15.0	−220
TDP^{3-}	−2469.9	−3182.6	−36	33.8	15.0	−220			
TTP^{4-}	−3330.2	−4175.2	−449				39.7	15.0	−220
$P_2O_7{}^{4-}$	−1920.2	−2299.1	−787				34.8	7.1	−223

[a] The standard state is the ideal solution of unit molality. G and H are in kJ mol^{-1} and $\overline{C}_p$ is in J mol^{-1} K^{-1}. Reaction (1) is: $YMP^{-} + HPO_4{}^{2-} \rightarrow YDP^{3-} + H_2O$ and reaction (2) is: $YDP^{2-} + HPO_4{}^{2-} \rightarrow YTP^{4-} + H_2O$.

Table 14
Standard formation properties of charged and complexed forms of nucleotides at 298.15 K

Compound	$\Delta_f H_i^\circ(T_r;\mathrm{aq})$ (kJ mol^{-1})	$\Delta_f G_i^\circ(T_r;\mathrm{aq})$ (kJ mol^{-1})	$\Delta_f S_i^\circ(T_r;\mathrm{aq})$ (J mol^{-1} K^{-1})	$\overline{C}_p^\circ\mathrm{aq},i$ (J mol^{-1} K^{-1})
H_2AMP	−1641.9	−1109.5	−1786	86
$HAMP^-$	−1623.6	−1069.5	−1858	23
AMP^{2-}	−1628.0	−1029.6	−2007	−103
$MgAMP$	−2085.0	−1501.3	−1957	132
H_2ADP^-	−2635.3	−1980.2	−2197	−121
$HADP^{2-}$	−2616.8	−1940.3	−2269	−184
ADP^{3-}	−2620.8	−1900.3	−2417	−310
$MgADP^-$	−3071.3	−2372.1	−2345	−138
$MgHADP$	−3072.5	−2412.0	−2215	51
H_2ATP^{2-}	−3621.7	−2851.0	−2585	−514
$HATP^{3-}$	−3605.2	−2811.0	−2664	−577
ATP^{4-}	−3609.3	−2771.1	−2811	−703
$MgHATP^-$	−4057.8	−3282.8	−2599	−405
$MgATP^{2-}$	−4057.2	−3242.8	−2731	−593
Mg_2ATP	−4514.6	−3714.6	−2683	−358
H_3GMP	−1907.9	−1351.3	−1868	585
H_2GMP^-	−1907.7	−1311.4	−2000	442
$HGMP^{2-}$	−1912.8	−1271.4	−2151	90
GMP^{3-}	−1879.3	−1231.5	−2173	−70
$MgHGMP$	−2371.5	−1743.2	−2107	325
H_3GDP^-	−2914.7	−2222.0	−2323	288
H_2GDP^{2-}	−2896.8	−2182.1	−2397	283
$HGDP^{3-}$	−2901.4	−2142.1	−2547	−97
GDP^{4-}	−2869.2	−2102.1	−2573	−333
$MgHGDP^-$	−3352.9	−2613.9	−2479	75
Mg_2GDP	−3352.5	−2653.8	−2343	518
H_2GTP^{2-}	−3894.9	−3093.6	−2687	253
$HGTP^{3-}$	−3888.1	−3053.6	−2799	133
GTP^{4-}	−3892.1	−3013.6	−2946	−256
$MgHGTP^-$	−4340.6	−3525.4	−2734	305
$MgGTP^{2-}$	−4339.9	−3485.4	−2866	−146
MgH_2GTP	−4797.2	−3957.2	−2817	89
H_2UMP^-	−2141.4	−1623.5	−1737	423
$HUMP^{2-}$	−2145.2	−1583.5	−1884	81
UMP^{3-}	−2113.3	−1543.5	−1911	−143
$MgUMP^-$	−2571.6	−2015.3	−1866	92
H_2UDP^-	−3163.4	−2541.6	−2085	492
$HUDP^{2-}$	−3168.7	−2501.7	−2237	122
UDP^{3-}	−3137.1	−2461.7	−2265	−116
$MgUDP^-$	−3589.5	−2933.5	−2200	56
H_2UTP^{2-}	−4155.8	−3421.8	−2462	523
$HUTP^{3-}$	−4162.7	−3381.9	−2619	102
UTP^{4-}	−4133.1	−3341.9	−2654	0
$MgHUTP^-$	−4615.33	−3853.7	−2555	274
$MgUTP^{2-}$	−4580.8	−3813.7	−2573	110
MgH_2UTP	−5038.2	−4285.5	−2525	345

Table 14 (*Continued*)

Compound	$\Delta_f H_i^\circ(T_r;\mathrm{aq})$ (kJ mol^{-1})	$\Delta_f G_i^\circ(T_r;\mathrm{aq})$ (kJ mol^{-1})	$\Delta_f S_i^\circ(T_r;\mathrm{aq})$ (J mol^{-1} K^{-1})	$\overline{C}_p^\circ\mathrm{aq},i$ (J mol^{-1} K^{-1})
$HCMP^-$	−1898.2	−1405.3	−1653	456
CMP^{2-}	−1902.9	−1365.3	−1803	108
MgCMP	−2371.2	−1832.3	−1807	92
H_2CDP^-	−2908.5	−2315.1	−1990	−20
$HCDP^{2-}$	−2889.9	−2275.1	−2062	−83
CDP^{3-}	−2894.0	−2235.2	−2210	−83
$MgCDP^-$	−3344.5	−2706.9	−2138	89
Mg_2CDP	−3345.7	−2746.9	−2008	152
H_2CTP^{2-}	−3902.6	−3186.6	−2402	−622
$HCTP^{3-}$	−3879.3	−3146.6	−2457	−622
CTP^{4-}	−3884.4	−3106.7	−2609	−622
$MgHCTP^-$	−4331.9	−3618.4	−2393	−450
$MgCTP^{2-}$	−4333.5	−3574.7	−2545	−512
MgH_2CTP	−4789.7	−4044.7	−2499	−277
H_3TMP	−2174.7	−1692.2	−1618	649
H_2TMP^-	−2184.1	−1652.3	−1784	503
$HTMP^{2-}$	−2188.7	−1612.3	−1933	160
TMP^{3-}	−2157.1	−1572.3	−1961	−78
MgHTMP	−2645.7	−2084.1	−1883	395
H_2TDP^-	−3194.3	−2561.3	−2123	153
$HTDP^{2-}$	−3175.8	−2521.3	−2195	90
TDP^{3-}	−3179.8	−2481.4	−2343	−36
$MgTDP^-$	−3630.3	−2953.1	−2272	136
Mg_2TDP	−3631.5	−2993.1	−2141	325
H_2TTP^{2-}	−3621.7	−2852.0	−2581	−514
$HTTP^{3-}$	−3605.2	−2812.0	−2660	−577
TTP^{4-}	−3609.3	−2772.1	−2808	−703
$MgHTTP^-$	−4057.8	−3283.8	−2596	−405
$MgTTP^{2-}$	−4057.2	−3243.8	−2728	−593
MgH_2TTP	−4514.6	−3715.6	−2680	−358

and complexation properties (Tables 9 and 10) and from data of Table 13, the properties of the charged species and the complexed species were calculated (Table 14).

5. Conclusion

Using the formation properties of purines and pyrimidines, the enthalpy, entropy and heat capacity of several nucleosides, nucleotides and nucleotide-phosphates were calculated in dilute aqueous solution. Starting from these properties and using dissociation and complex formation constants, the transformed properties of these compounds were calculated at given pH and complex ion concentrations. The influence of pH and complex ion concentration on these properties were also studied. Comparison with some enzymatic equilibrium constants shows a close agreement with the available data. We stress that all these formation properties are calculated from a single reference state of the elements [41]. The formulation and resolution of the system of equations representative of the multiple chemical equilibria in aqueous solution correctly account for the influence of independent variables such as pH or divalent ion concentrations. This afforded an optimal reconciliation of the available literature data, and allows proper calculation of metabolic reaction properties as a function of actual intracellular concentrations.

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