119. Binding of AMP, ADP, and ATP Nucleotides by Polyammonium Macrocycles

by **Mir Wais Hosseini** and **Jean-Marie Lehn***
Institut Le Bel, Université Louis Pasteur, 4, rue Blaise Pascal, F–67000 Strasbourg[1])

(3. VI. 87)

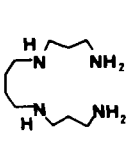
The macrocyclic polyamines **4–6**, when protonated, bind strongly and selectively nucleotides (AMP, ADP, ATP) and pyrophosphate in aqueous solution. The stoichiometry of the complexes formed was determined by titration experiments followed by ^{31}P-NMR spectroscopy. Compounds **4** and **5** form 1:1 complexes with ATP, ADP, and pyrophosphate, whereas **6** forms complexes with ATP and ADP involving 2 nucleotides and 1 receptor molecule. The stability constants of these complexes have been determined by pH-metric measurements. At pH 7, both **5** and **6** give complexes of mainly the fully protonated species $\mathbf{5}\cdot 6H^+$ and $\mathbf{6}\cdot 8H^+$, whereas **4** yields predominantly complexes of $\mathbf{4}\cdot 5H^+$ and $\mathbf{4}\cdot 4H^+$.

Introduction. – In view of the fundamental role played by anions in chemical as well as biological processes, the binding of organic and inorganic anionic substrates by synthetic receptors is of wide interest. Indeed, numerous enzymes act on substrates bearing phosphate and carboxylate groups. The nucleotides adenosine triphosphate (ATP), adenosine diphosphate (ADP), and adenosine monophosphate (AMP) play a most important role in the energy-storage and -transfer processes in living organisms.

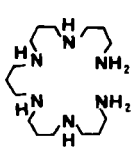
The recent development of anion complexation by synthetic polyammonium molecules opens the way to the design of molecular receptors capable of binding selectively and strongly anionic substrates and thus extends supramolecular chemistry to both cations and anions [1].

Macrocyclic polyamines, when protonated, have been shown to complex a variety of inorganic and organic anions [2–8] (for a review, see [9]). In particular, they bind nucleotides and polyphosphates [2] [3] [8]. The binding [10] [11] and transport [12] of nucleotides by polycyclic polyammonium receptors have been reported. Biological polyamines, *i.e.* putrescine, spermidine, and spermine, also bind nucleotides [13].

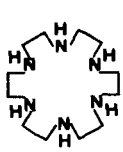
Recently, the catalysis of ATP, ADP, and pyrophosphate hydrolysis by macrocyclic polyamines has been reported [14–16]. Furthermore, it has been demonstrated that the



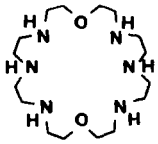
1



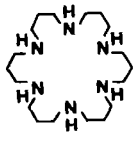
2



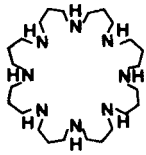
3



4



5



6

[1]) U. A. 422 of the CNRS.

macrocyclic compound **4**, possessing simultaneously binding (ammonium) and reactive (amine) sites, catalyses the acetyl phosphate breakdown and, more interestingly, the formation of pyrophosphate [17].

We now describe a study of the complexation of nucleotides and pyrophosphate (PP) by the acyclic and macrocyclic polyamines **1–6**.

Results and Discussion. – *Binding Stoichiometry.* For the binding studies involving nucleotides and polyphosphates, ^{31}P-NMR spectroscopy is used as a powerful obser-

Table 1. *^{31}P-NMR Chemical Shifts of Substrates ATP and ADP on Complexation by Polyamines* **1**, **5**, *or* **6**, *and Stoichiometry of the Complexes at pH 6.5*[a])

Polyamine (stoichiometry)[b])	ATP					Polyamine	ADP					
	P-Atom[c])	Δ[d]) for R[e])					P-Atom[c])	Δ[d]) for R[e])				
		0.25	0.50	1.0	1.50			0.25	0.50	0.75	1.0	1.50
1 (1:1)	α	0.05	0.05	0.05	0.09	**5** (1:1)	α	0.51	0.94	1.17	1.34	1.34
	β	0.21	0.30	0.50	0.50		β	0.53	1.08	1.41	1.54	1.54
	γ	0.54	0.90	1.65	1.79							
5 (1:1)	α	−0.12	−0.22	−0.39	−0.43	**6** (2:1)	α	0.16	0.36	0.33	0.32	0.32
	β	0.25	0.71	1.21	1.21		β	1.09	1.53	1.82	1.94	1.97
	γ	0.31	1.02	1.73	1.69							
6 (2:1)	α	−0.03	−0.07	−0.09	−0.12							
	β	0.21	0.52	0.54	0.50							
	γ	0.69	1.75	1.85	1.83							

[a]) At 36.4 MHz; chemical shifts are given in ppm using H_3PO_4 (85%) as external reference; in D_2O/H_2O 2:8 at 25°.

[b]) The plot of Δ *vs.* R indicates the stoichiometry (substrate per ligand).

[c]) Phosphate moiety at α, β, or γ position from ribose.

[d]) Δ (in ppm) = δ (complex) − δ (free substrate). For $R = 0$, δ_{ATP} (in ppm): −11.18 (P(α)); −22.52 (P(β)); −8.74 (P(γ)); δ_{ADP} (in ppm): −11.10 (P(α)); −8.96 (P(β)).

[e]) R = [receptor]/[substrate]; [substrate] = 0.01M; all compounds were used as their HCl salt.

Table 2. *^{31}P-NMR Chemical Shifts of Substrate ATP on Complexation by Polyamine* **2** *and* **3**, *and Stoichiometry of the Complexes*[a])

Polyamine (stoichiometry)[b])	pH	P-Atom[c])	Δ[d]) for R[e])						
			0	0.2	0.4	0.6	0.8	1.0	1.5
2 (1:1, 2:1)	7	α	−10.33	−0.03	−0.01	−0.03	−0.03	−0.05	−0.05
		β	−21.23	0.06	0.13	0.11	0.13	0.13	0.13
		γ	− 6.55	0.28	0.45	0.47	0.48	0.53	0.51
3 (1:1, 2:1)	3.5	α	−10.63	0.22	0.36	0.42	0.45	0.48	0.51
		β	−22.31	0.63	1.13	1.35	1.43	1.46	1.53
		γ	−10.09	0.53	0.93	1.19	1.37	1.47	1.50
3 (1:1, 2:1)	6.5	α	−10.38	−0.04	0.08	0.14	0.24	0.21	0.27
		β	−21.60	0.48	0.92	1.16	1.25	1.31	1.35
		γ	− 7.70	0.76	1.30	1.71	1.80	1.92	2.02

[a]) At 81 MHz; chemical shifts are given in ppm using H_3PO_4 (85%) as external reference; in D_2O/H_2O 1:9 at 25°.

[b]) The plot of Δ *vs.* R indicates a mixture of complexes containing 1 ATP per receptor and 2 ATP per receptor.

[c]) Phosphate moiety at α, β, or γ position from ribose.

[d]) Δ (in ppm) = δ (complex) − δ (free substrate).

[e]) R = [receptor]/[substrate]; [substrate] = 0.01M; all compounds were used as their HCl salt.

Table 3. *^{31}P-NMR Chemical Shifts of Substrates ATP, ADP, and PP on Complexation by Polyamine* **4**[a])

Substrate (stoichiometry)[b])	pH	P-Atom[c])	Δ[d]) for R[e])						
			0	0.2	0.4	0.6	0.8	1.0	1.5
ATP (1:1)	3.5	α	−10.63	0.09	0.12	0.11	0.13	0.13	0.13
		β	−22.31	0.59	1.04	1.56	2.06	2.33	2.33
		γ	−10.09	0.92	1.79	2.89	3.89	4.46	4.44
ATP (1:1)	6.5	α	−10.38	−0.04	0.0	0.0	0.0	0.02	0.02
		β	−21.60	0.50	0.82	1.20	1.43	1.60	1.58
		γ	− 7.70	0.58	1.07	1.57	1.87	2.04	2.11
			Δ[d]) for R[e])						
			0	0.242	0.484	0.726	0.967	1.209	1.81
ADP (1:1)	3.5	α	−10.63	0.37	1.06	1.69	1.97	2.13	2.13
		β	−10.02	0.56	1.71	2.81	3.29	3.57	3.59
ADP (1:1)	6.5	α	−10.41	0.38	0.77	1.00	1.09	1.18	1.22
		β	− 8.15	0.95	1.40	1.72	1.81	1.82	1.85
			Δ[d]) for R[e])						
			0	0.2	0.4	0.6	0.8	1.0	1.5
PP (1:1)	7.5		− 6.90	0.17	0.47	0.74	1.01	1.18	1.22

[a]) In D_2O/H_2O 1:9 at 25°; at 81 MHz; chemical shifts are given in ppm using H_3PO_4 (85%) as external reference.
[b]) The plot of Δ *vs.* R indicates complexes formed between 1 receptor and 1 substrate.
[c]) Phosphate moiety at α, β, or γ position form ribose.
[d]) Δ (in ppm) = δ (complex) − δ (free substrate).
[e]) R = [receptor]/[substrate]; [substrate] = 0.01M; the receptor was used as its hexahydrochloride salt.

vation technique, as complexation of phosphate-containing molecules by protonated polyamines induces shifts in the ^{31}P-NMR signals. In the presence of protonated forms of compounds **1–6**, the P(α) signal of ATP is almost unaffected, whereas the P(β) and particularly the terminal-phosphate P(γ) signals are considerably shifted. The AMP is only weakly affected. The results obtained for ATP, ADP, and PP titration by acyclic and macrocyclic polyamines **1–6** are listed in *Tables 1–3*. An example of the variation of the ^{31}P-NMR chemical shifts of ATP as a function of the [**4**]/[ATP] ratio is given in *Fig. 1*. The

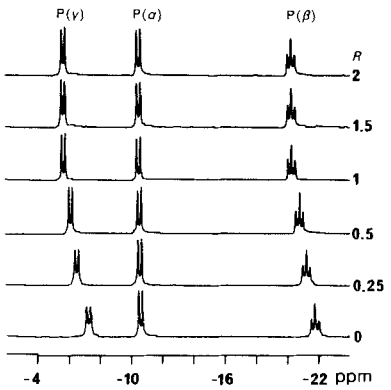


Fig. 1. *^{31}P-NMR spectra of ATP as a function of increasing ligand/substrate ratio* R (R = [**4**]/[ATP]) *at pH 7.* D_2O/H_2O 1:9 solution, 0.01M ATP; 20°.

maximum shift is observed with an equimolar mixture of polyamine **4** and ATP, demonstrating a 1:1 stoichiometry.

In the absence of complexing agent, increasing the pH of a solution containing ATP from 3.5 to 7 shows almost no effect on the ^{31}P-NMR chemical shift of both the P(α) and P(β) signals, but produces a significant shift of the terminal-phosphate P(γ) signal (*Fig. 2*). This observation seems reasonable since the first protonation of ATP ($pK_a \approx 6.5$) occurs at the most negatively charged (2-) terminal phosphate centre [18]. On the other hand, increasing the pH of a solution containing both ATP and polyamine **4** from 2.5 to 8.5 produces no further shifts of the ^{31}P-NMR signals of the complexed ATP. Thus, binding of ATP by protonated **4** significantly lowers the pK_a's of ATP and prevents the protonation of its terminal phosphate over the pH range studied. One notices that whereas the protonation of ATP causes a shielding of the terminal-phosphate signal, binding of ATP by polyammonium receptors causes a deshielding of both P(β) and P(γ) phosphate signals (*Fig. 2*).

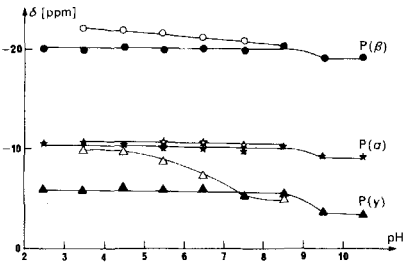


Fig. 2. *^{31}P-NMR chemical shifts of the α-, β-, and γ-phosphate signals of free ATP (○,☆,△) and ATP complexed by* **4** *(●,★,▲) as a function of pH.* D_2O/H_2O 1:9 solution.

The plot of [receptor]/[substrate] ratio (*R*) *vs.* the difference in the chemical shifts (Δ in ppm) between the complexed and free substrate leads to titration curves which allow to study the stoichiometry of the complexes. Three examples of such a plot are given in *Fig. 3*. In agreement with published results using another method [13], at pH 6.5, spermine (**1**) forms 1:1 complexes with ATP (*Table 1*). At the same pH value, the acyclic hexaamine **2** and the macrocycle **3** both give a mixture of complexes containing either 1 or 2 ATP units and 1 receptor (*Table 2*). The 24-membered macrocyclic hexaamine **4** forms 1:1

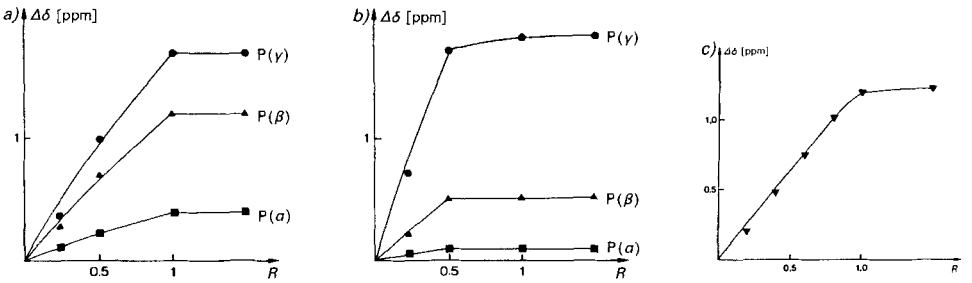


Fig. 3. *^{31}P-NMR shifts ($|\Delta\delta|$) of the α-, β-, and γ-phosphate signals of ATP and of pyrophosphate as a function of increasing ligand/substrate ratio* R; *a)* ATP and **5** in D_2O/H_2O 1:4 (0.02M ATP, pH 6.5, 20°); *b)* ATP and **6** in D_2O/H_2O 1:4 (0.02M ATP, pH 6.5, 20°); *c)* PP and **4** in D_2O/H_2O 1:4 (0.03M PP, pH 7.5, 25°).

complexes with ATP at pH 3.5, 6.5, and 7 (*Fig. 1*), with ADP at pH 3.5 and 6.5, and also with PP (*Fig. 3c*) at pH 7.5 (*Table 3*). The same holds at pH 6.5 for **5** with both ATP (*Fig. 3a*) and ADP (*Table 1*). On the other hand, the 32-membered macrocyclic octaamine **6** which may be considered as a double cyclic analogue of spermine (**1**) forms complexes with ATP and ADP at pH 6.5 involving two ATP or ADP units and one receptor **6** (*Fig. 3b*). At pH 7.5, a mixture of 1:1 and 2:1 complexes of ATP and ADP with spermine (**1**) has been reported [13]. Finally, one must note that ^{31}P-NMR studies such as those reported here yield information on the predominant species present in solution, but do not exclude minor species of different compositions.

Stability of the Complexes. The stability constants log K_s^n corresponding to the equilibria of the polyammonium ions H_nL^{n+} (L = **4**–**6**) with AMP, ADP, and ATP anions A^{m-} (*Eqns. 1* and *2*) have been determined by pH-metric titration (see *Exper. Part*); they are listed in *Table 4*. As an example, the titration curve for **5** is shown in *Fig. 4*. The stoichio-

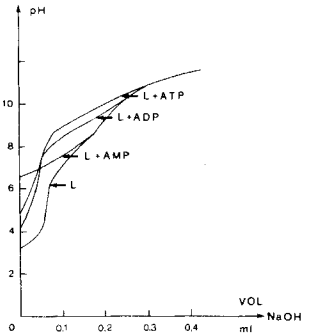


Fig. 4. *pH-Metric titration curves of ATP, ADP, and AMP in the presence of* **5** (= L). Titration by 0.1N NaOH of a solution containing 1mM **5** as its hydrochloride salt, 0.1M NMe_4Cl, 1mM HCl, and 5mM AMP or 2.5mM ADP or 1.5mM ATP. L refers to the titration of 1mM **5** as its hydrochloride salt.

Table 4. *Stability Constants log* K_s^n (±0.20) *for Nucleotide-Anion Binding by the Macrocyclic Polyammonium Receptor Molecules* **4**–**6** *in Aqueous Solutions*[a])

Receptor (L)[b])	Complexes					
	($L \cdot nH^+$, AMP)		($L \cdot nH^+$, ADP)		($L \cdot nH^+$, ATP)	
	n[c])	log K_s^n	n[c])	log K_s^n	n[c])	log K_s^n
4	4	2.85	4	3.40	4	4.80
	5	5.50	5	6.20	5	8.15
	6	6.95	6	8.30	6	11.00
			7	5.60	7	7.85
					8	6.75
5	4	1.75	4	4.0	4	5.00
	5	2.75	5	4.50	5	6.85
	6	3.40	6	6.50	6	8.90
6	5	(5.00)[d])	5	(7.00)	5	(8.00)
	6	(5.55)	6	(8.10)	6	(9.95)
	7	(5.90)	7	(9.15)	7	(11.50)
	8	(7.20)	8	(10.20)	8	(12.80)

[a]) The log K_s (in $l \cdot mol^{-1}$) values are determined in the presence of either 0.1M NMe_4Cl (**5** and **6**) or 0.1M TsONa (**4**) at 25°: see *Eqn. 1* for definition of K_s^n.

[b]) Compound **4** was used as its hexakis(*p*-toluenesulfonate) salt, **5** and **6** as their hydrochloride salts.

[c]) n = Number of protons involved in complexes of the type (receptor $\cdot nH^+$, anion).

[d]) Values in parentheses are calculated for 2 anions per receptor stoichiometries.

metries of all complexes were determined by ^{31}P-NMR titration experiments as discussed above. The stability constants for the complexes of ATP with spermine (**1**) [13] and hexacyclen (**3**) [3] have been reported. In the latter case, a 1:1 stoichiometry was assumed. Titration experiments followed by ^{31}P-NMR showed that a mixture of 1:1 and 2:1 complexes is present in solution (*Table 2*).

$$L + nH^+ + pA^{m-} \rightleftharpoons H_nLA_p^{(n-mp)+} \quad (1)$$

$$K_s^n = \frac{[H_nLA_p^{(n-mp)+}]}{[H^+]^n[L][A^{m-}]^p} \quad (2)$$

It may be first noted that since compounds **1–6** are anion receptors, the log K_s^n values found depend on the anion present in the supporting electrolyte. The latter was chosen so as to minimize such effects of the medium. Although complexation of Cl^- ion is probably weak, it nevertheless affects the data so that the stability constants determined in its presence are apparent values. The weak Cl^- binding was also observed by ^{35}Cl-NMR studies [19]. In order to minimize these interactions, sodium *p*-toluenesulfonate (TsONa) was used as the supporting electrolyte in the presence of **4**.

Compounds **4–6** bind the nucleotides with high stability and selectivity in aqueous solution. The most stable complexes are formed between the most charged species. The log K_s^n values for the tetraprotonated forms of spermine (**1**) range from 2.55 for AMP to 3.97 for ATP [13], whereas in the case of fully protonated compounds **4–6**, they range from 3.4 (**5**·6H$^+$,AMP^{2-}) to 11 (**4**·6H$^+$,ATP^{4-}). The stability constants for **3**·3H$^+$ and AMP^{2-}, ADP^{3-}, or ATP^{4-}, calculated assuming a 1:1 stoichiometry, have been reported [3] to lie in the range of 3.2 for AMP^{2-} to 6.39 for ATP^{4-}.

The lowest pK_n values corresponding to full protonation are 3.4 for polyamine **4** and *ca.* 6.5 for **5** and **6** [20]. On the other hand, the first protonation of free AMP, ADP, and ATP occurs at pH *ca.* 6–6.5. Since the complexation increases the pK_n values of the receptor and lowers the pK_a values of the substrates, the complexes formed by compounds **5** and **6** at neutral pH are expected to be of the type (L·nH$^+$,AXP^{m-}), with L = **5** or **6**, n = 6 or 8, respectively, and X = M,D,T, m = 2,3,4.

In the case of **4**, since its pK_n of full protonation in the absence of substrate is much lower than the pK_a of free ATP, different types of complexes may coexist in solution.

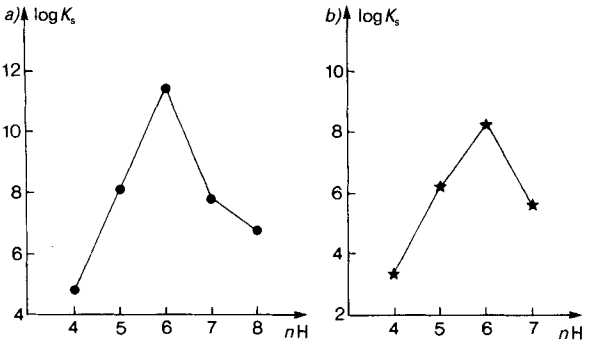


Fig. 5. *Graphical representation of the stability constants log* K_s *of the complexes formed by the polyammonium macrocycle derived from* **4** *(L) with* a) *ATP and* b) *ADP as a function of* n, *the total number of* H^+ *present in complexes of the type (***4**,nH^+,AXP^{m-}*) with X = D/*m = *3 and X = T/*m = *4*

Fig. 5 shows the variation of the stability constants log K_s^n with increase of the number n of protons involved in the complexes of ADP and ATP with **4**. In both cases, the values of the stability constants drop when either the number of positively charged binding sites on the receptor or the number of negatively charged centres on the substrate decreases. For ATP (*Fig. 5a*), the smaller decrease in the stability constants observed between $n = 7$ and 8 is probably due to the fact that the second protonation of ATP ($pK_{a2} \approx 4$) occurs at the amino group of adenine [18], separate from the polyphosphate chain. A representation of the distribution of different species present in solution, in the pH range 2–11, was reported [14]. The sum of all complexes in solution is constant and represents *ca.* 100% of **4** from pH 2 to 8; at higher pH values, partially protonated forms of compound **4** accumulate. At low pH, the complexes present in solution are of the type ($\mathbf{4}\cdot 6H^+,HAXP^{m-}$) with $X = D/m = 2$ and $X = T/m = 3$ and of the type ($\mathbf{4}\cdot 6H^+,H_2ATP^{2-}$). The complexation of the singly charged H_2ADP^- and H_3ATP^- anions is expected to be rather weak and has not been taken into account in the calculations. At pH values higher than the first pK_a of AXP (X = M,D,T), the complexes present are of the type ($\mathbf{4}\cdot nH^+,AXP^{m-}$) with $n = 4,5,6$, $X = M/m = 2$, $X = D/m = 3$, and $X = T/m = 4$. In the intermediate pH range, complexes of the type ($\mathbf{4}$,nH^+,AXP^{m-}) with $n = 5,6$, $X = M/m = 2$, $X = D/m = 3$, and $X = T/m = 4$ exist in solution. It is impossible to know definitely whether these complexes are of the type ($\mathbf{4}\cdot 6H^+,AXP^{m-}$) or ($\mathbf{4}\cdot 5H^+,HAXP^{(m-1)-}$) for $n = 6$ and ($\mathbf{4}\cdot 5H^+,AXP^{m-}$) or ($\mathbf{4}\cdot 4H^+,HAXP^{(m-1)-}$) for $n = 5$. But since the stability constant for the complex containing 7 protons ($\mathbf{4}\cdot 6H^+,HTAP^{3-}$) is lower by a factor of 10^3 than the stability constant calculated for the complex with 6 protons and since the more stable complexes are generally formed between the most charged partners, it seems reasonable to propose that the protons are more likely located on the macrocycle, leading to maximum interactions between 6 ammonium binding sites and 4 negative charges on the polyphosphate chain. The same should hold for ADP. In addition, the ^{31}P-NMR chemical shifts of ATP in the presence of **4** are constant in the pH range from 2.5 to 8.5, indicating that the polyphosphate chain of ATP is probably not affected by decreasing the pH (*Fig. 2*) and remains tetra-anionic.

Structure of the Complexes. The results presented above provide information on the composition and stability of the complexes formed by the macrocyclic receptors **3–6** with polyphosphate anionic substrates. However, they do not allow to define the geometry of these species. A detailed knowledge of the structures would be of much interest for understanding both the origin of binding strength and the eventual reactivity of the complexes. Such information could be obtained from spectroscopic studies, for instance by NMR [19a,b], or from radiocrystallographic structure determinations if suitable crystals can be grown. Molecular models indicate that the complexes detected are at least compatible with the sizes and shapes of the macrocyclic receptors and of the nucleotide substrates (for the representation of a hypothetical structure of the ($\mathbf{4}\cdot 6H^+,ATP^{4-}$) complex, see [14]).

Conclusion. – The present results demonstrate the ability of macrocyclic polyammonium receptor molecules to strongly bind nucleotides and polyphosphates, giving complexes of different stoichiometry depending on the case. They extend the complexation chemistry of anions to a class of anionic substrates which plays a fundamental role in the bioenergetics of all living organisms.

Experimental Part

General. The syntheses of acyclic and macrocyclic polyamines **2**, **5**, and **6** [20] and **4** [21] have been described. Compounds **1** and **3** are commercially available. Polyamine **3** was purchased as its trisulfate salt and was converted to its hexahydrochloride salt by passage over an anion-exchange column. The sodium salts of ATP, ADP, and AMP were obtained from *Boehringer*, Mannheim. All other chemicals used were high-purity commercial reagents. ^{31}P-NMR spectra: *Bruker-WP90* (36.43 MHz) and *Bruker-SY200* (81.015 MHz) spectrometers; chemical shifts are (+, downfield) from 85% H_3PO_4 as external reference.

Stoichiometry of the complexes was studied by following ^{31}P-NMR shifts as a function of receptor/nucleotide ratio. The pH of the soln. (D_2O/H_2O 1:9 or 2:8) was adjusted to the desired value at 25° with 5M NaOH or HCl and was not corrected for the effect of D_2O.

Stability Constants (K_s^n) of the complexes were determined under N_2 by titration with 0.1N NaOH of a soln. containing 10^{-3}M of the HCl salt of **5** and **6** or the *p*-toluenesulfonic acid (TsOH) salt of **4** and 1.5, 2.5, 5×10^{-3}M of ATP, ADP, and AMP respectively, in the presence of 0.1M NMe_4Cl or TsONa. Data analysis for all titration results was performed following the same procedures as previously [4] using the computer program SCO75. In order to check the validity of the K_s^n values calculated, the model proposed for calculation (type of equilibria and of species assumed to be present in soln.) was varied. The models giving a convergence with an acceptable fit (standard deviation $< 5 \times 10^{-3}$ and shift for each value $= 0$) correspond to the values reported in *Table 4*. The stability constants for ATP-binding by spermine (**1**) were also determined by the method used in this study and were in good agreement with the published results obtained by another method [13].

REFERENCES

[1] J. M. Lehn, 'Biomimetic Chemistry', Eds. N. Ise and Z. I. Yoshida, Kodansha Ltd., Tokyo, Elsevier, Amsterdam, 1983, p. 163; *Science* **1985,** *227,* 849.

[2] B. Dietrich, M. W. Hosseini, J. M. Lehn, R. B. Sessions, *J. Am. Chem. Soc.* **1981,** *103,* 1282.

[3] E. Kimura, A. Sakonaka, T. Yatsunami, M. Kodama, *J. Am. Chem. Soc.* **1981,** *103,* 3041; E. Kimura, M. Kodama, T. Yatsunami, *ibid.* **1982,** *104,* 3182.

[4] M. W. Hosseini, J. M. Lehn, *J. Am. Chem. Soc.* **1982,** *104,* 3525; *Helv. Chim. Acta* **1986,** *69,* 587.

[5] J. Cullinane, R. I. Gelb, T. N. Margulis, L. J. Zompa, *J. Am. Chem. Soc.* **1982,** *104,* 3048; R. I. Gelb, B. T. Lee, L. J. Zompa, *ibid.* **1985,** *107,* 909; R. I. Gelb, L. M. Schwartz, L. J. Zompa, *Inorg. Chem.* **1986,** *25,* 1527.

[6] F. Peter, M. Gross, M. W. Hosseini, J. M. Lehn, R. B. Sessions, *J. Chem. Soc., Chem. Commun.* **1981,** 1067; F. Peter, M. Gross, M. W. Hosseini, J. M. Lehn, *J. Electroanal. Chem.* **1983,** *144,* 279.

[7] N. I. Manfrin, N. Sabbatini, L. Moggi, V. Balzani, M. W. Hosseini, J. M. Lehn, *J. Chem. Soc., Chem. Commun.* **1984,** 555; N. I. Manfrin, L. Moggi, V. Castelvetro, V. Balzani, M. W. Hosseini, J. M. Lehn, *J. Am. Chem. Soc.* **1985,** *107,* 6888.

[8] J. F. Marecek, C. J. Burrows, *Tetrahedron Lett.* **1986,** *27,* 5943.

[9] F. Vögtle, *Topics Curr. Chem.* **1981,** *98,* 143; J. L. Pierre, P. Baret, *Bull. Soc. Chim. Fr. II* **1983,** 367; E. Kimura, *Topics Curr. Chem.* **1985,** *128,* 113.

[10] F. P. Schmidtchen, *Chem. Ber.* **1981,** *114,* 597; *Topics Curr. Chem.* **1986,** *132,* 101.

[11] B. Dietrich, J. Guilhem, J. M. Lehn, C. Pascard, E. Sonveaux, *Helv. Chim. Acta* **1984,** *67,* 91.

[12] I. Tabushi, J. I. Imuta, N. Seko, Y. Kobuke, *J. Am. Chem. Soc.* **1978,** *100,* 6288; I. Tabushi, Y. Kobuke, J. I. Imuta, *ibid.* **1980,** *102,* 1744.

[13] C. Nakai, W. Glinsmann, *Biochemistry* **1977,** *16,* 5636; W. H. Voige, R. I. Elliott, *J. Chem. Educ.* **1982,** *59,* 257.

[14] M. W. Hosseini, J. M. Lehn, M. P. Mertes, *Helv. Chim. Acta* **1983,** *66,* 2454; *ibid.* **1985,** *68,* 818.

[15] M. W. Hosseini, J. M. Lehn, L. Maggiora, K. B. Mertes, M. P. Mertes, *J. Am. Chem. Soc.* **1987,** *109,* 537.

[16] P. G. Yohannes, M. P. Mertes, K. B. Mertes, *J. Am. Chem. Soc.* **1985,** *107,* 8288.

[17] M. W. Hosseini, J. M. Lehn, *J. Chem. Soc., Chem. Commun.* **1985,** 1155; M. W. Hosseini, J. M. Lehn, *J. Am. Chem. Soc.* **1987,** *109,* in press.

[18] M. Matthies, G. Zundel, *J. Chem. Soc., Perkin Trans. 2* **1977,** 1824.

[19] a) A. Zahidi, Thèse de Doctorat ès Sciences, Université Louis Pasteur, Strasbourg, 1986; b) M. W. Hosseini, J. P. Kintzinger, J. M. Lehn, A. Zahidi, unpublished results; c) see also, J. P. Kintzinger, J. M. Lehn, E. Kauffmann, J. L. Dye, A. I. Popov, *J. Am. Chem. Soc.* **1983,** *105,* 7549.

[20] B. Dietrich, M. W. Hosseini, J. M. Lehn, R. B. Sessions, *Helv. Chim. Acta* **1983,** *66,* 1262.

[21] J. Comarmond, P. Plumeré, J. M. Lehn, Y. Agnus, R. Louis, R. Weiss, O. Kahn, I. Morgenstern-Badarau, *J. Am. Chem. Soc.* **1982,** *104,* 6330.

[22] I. G. Sayce, *Talanta* **1968,** *15,* 1397; *ibid.* **1971,** *18,* 653.