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X-Ray Photoelectron Spectroscopy of Porphyrins

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Abstract: The nitrogen 1s binding energies of a series of porphyrins and several platinohematoporphyrin complexes obtained by x-ray photoelectron spectroscopy (XPS) are presented and discussed. The influence of different substituents at the periphery of the porphyrins has been studied; however, no significant change could be detected between the N_{1s} binding energies of the porphyrins studied. A value of 2 eV has been found between aza and pyrrole type nitrogen binding energies. The nature of the sitting-atop (SAT) complex reported in the literature is discussed. XPS gives strong evidence for the existence of the SAT complex, *cis*-PtCl₂H₂(Hemato-IX). Two types of nitrogens located at 399.9 eV for N-H and at 398.6 eV for N→Pt have been found in the SAT complex. Furthermore, the N_{1s} region for the platinohematoporphyrin Pt(Hemato-IX) shows that the four nitrogens are equivalent. A value of 399.4 eV is found for the N_{1s} binding energy of N-Pt where platinum is covalently bound to hemato porphyrin. The difference between the two types of nitrogen binding energies tends to zero in the series, H₂(Hemato-IX) ($\Delta E = 2.3$ eV) → *cis*-PtCl₂H₂(Hemato-IX) ($\Delta E = 1.3$ eV) → Pt(Hemato-IX) ($\Delta E = 0$ eV), indicating a tendency toward equivalency upon platinum insertion.

Introduction

X-Ray photoelectron spectroscopy proved to be a useful tool for the differentiation of nitrogen atoms in porphyrins.¹⁻⁴ Two types of nitrogens are found in porphyrin free bases, the aza type, whose N_{1s} binding energy is near 398 eV, and the pyrrole type of 400 eV. On metal complexation the four nitrogen atoms become equivalent with an N_{1s} energy at 399 eV.

A very interesting problem concerning the chemistry of metalloporphyrins is the knowledge of the incorporation process of the metal inside the four nitrogen atoms of the porphyrin. This field was recently reviewed by Hambricht.⁵ It is now generally admitted that a certain type of interaction takes place between the porphyrin and the metal before its insertion in the porphyrin plane. The intermediate compounds called "sitting-atop" complexes were studied either in solution^{6,7} or in the solid state.⁸⁻¹¹ A controversy is still existing for the SAT evidence in solution¹² since in some cases the green coloration generally attributed to the SAT was in fact due to the mono- and diacid forms of the porphyrin.⁶ The mono-, di-, and trimetallic porphyrins with unusual geometries were described by Tsutsui and Taylor.¹³

The problem of the SAT configuration is not yet completely understood. This study provides evidence for the existence of a SAT complex, *cis*-PtCl₂H₂(Hemato-IX), obtained during the preparation of the platinohematoporphyrin, Pt(Hemato-IX). The influence of the two kinds of platinum fixation on the nitrogen atoms is clearly demonstrated with N_{1s} binding energies in a series of compounds.

Experimental Section

Hematoporphyrin IX, H₂(Hemato-IX), was bought from Nutritional Biochemicals Co. The platinum porphyrin complexes were prepared following the method of Macquet and Theophanides.⁸ The

different porphyrins used in the present study were purchased from Calbiochem, California [(H₂(Copro-I-TME), H₂(Copro-III-TME)), Man-Win, Washington, D.C. [(H₂(TPyP), H₂(Deut-IX-DME), H₂(TPP)), and Sigma, Missouri [H₂(Proton-IX-DME)]. K₂[PtCl₄] from Johnson Matthey and Mallory Ltd. was recrystallised twice before use.

X-Ray photoelectron spectra were recorded on a standard 650 Du Pont spectrometer with Mg K α x-ray target. The reference line was the carbon line at 285 eV. The compounds were run as films evaporated from chloroform solution on SiO₂ (1/4-in. disk). Under the experimental conditions employed in the present study, the full widths at half maximum (fwhm) of nitrogen peaks have been found to be 2.0 ± 0.1 eV. The accuracy of the binding energies was ±0.2 eV and no significant instrument drift was detected. The nitrogen spectra were curve fitted by a least-squares computed program using a Lorentzian function with a fwhm of 2.0 eV.

It must be noted that the two diacid species, [H₄(Hemato-IX)]²⁺(Cl⁻)₂ and [H₄(Hemato-IX)]²⁺[PtCl₄]²⁻, studied by Raman spectrophotometry¹⁴ were found to be unstable toward x-ray irradiation. This may be due to partial denaturation under vacuum or to radiation damage.

Results

The different hematoporphyrin compounds used in the present study are given in Figure 1. For this series, binding energies of nitrogen, platinum, and chlorine atoms are reported in Table I. The N_{1s} spectrum of the starting porphyrin, H₂(Hemato-IX), is shown in Figure 2 and a comparison between the different nitrogen 1s binding energies in this series is presented in Figures 3 and 4. The binding energies were all determined from a visual inspection of the spectra with an accuracy of ±0.2 eV. In order to study the substituent effect at the periphery of the porphyrin on the N_{1s} binding energies, a series of porphyrins was considered. Their structural representation and the different N_{1s} binding energies are found in Figure 5 and in Table II. Deconvolution spectra of porphyrins

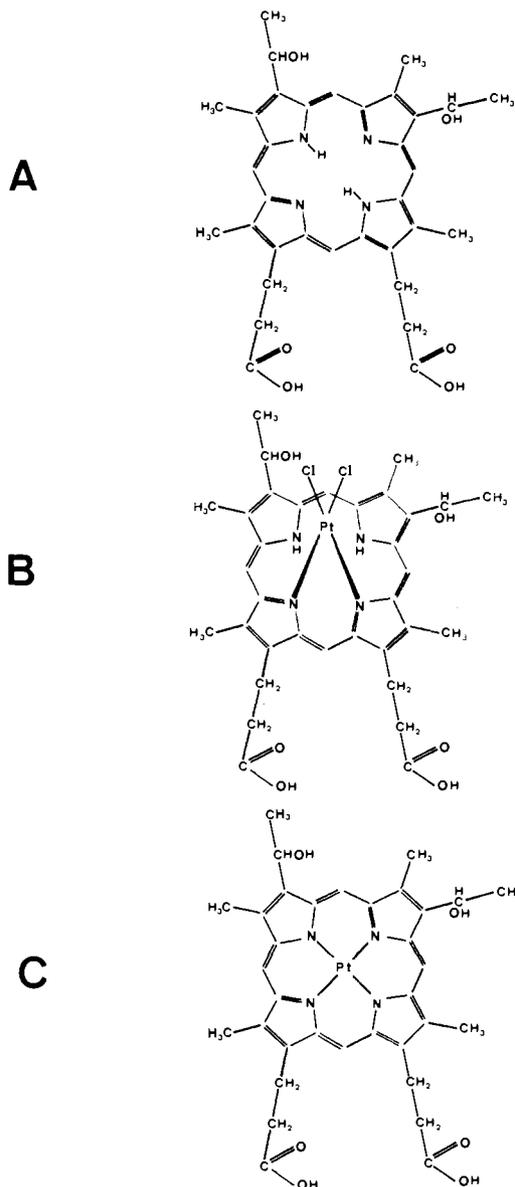


Figure 1. The structural representations of (A) hematoporphyrin IX, H₂(Hemato-IX); (B) the SAT complex, *cis*-PtCl₂H₂(Hemato-IX); (C) the platinohematoporphyrin IX complex, Pt(Hemato-IX).

Table I. Binding Energies (eV) of Various Core Levels in Hematoporphyrin Compounds

compd	N _{1s}	ΔE _{N_{1s}}	Pt _{4f_{7/2}}	Cl _{2p}
H ₂ (Hemato-IX)	400.2 397.9	2.3		
<i>cis</i> -PtCl ₂ H ₂ (Hemato-IX)	399.9 398.6	1.3	73.0	198.5
Pt(Hemato-IX)	399.4 ^a	0	73.3	

^a Only one N_{1s} band.

I, II, and VI are given in Figure 6 for the nitrogen atoms. It must be noted that the intensities of the two N_{1s} peaks are similar for the porphyrins considered, except in H₂(TPyP), where the N_{1s} band located around 399 eV is broad.

Discussion

The location of inner hydrogen atoms in porphyrins was for a long time a subject of controversy. This topic was recently reviewed by Smith.^{5b} Three kinds of positions for these hy-

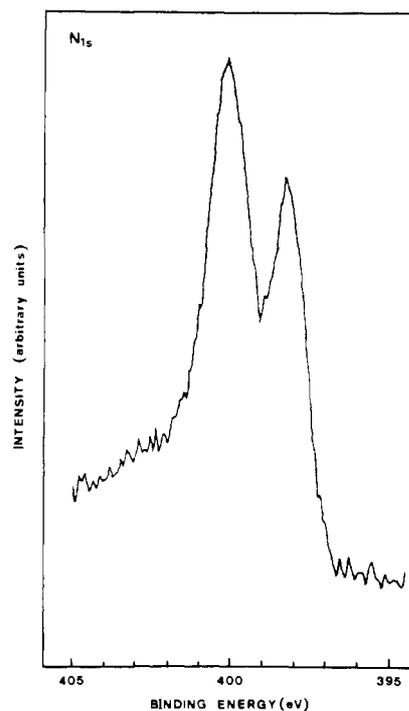


Figure 2. The nitrogen 1s spectrum for H₂(Hemato-IX) using Mg Kα x ray. The binding energy scale was corrected assuming the binding energy of the lowest carbon 1s peak to be 285 eV.

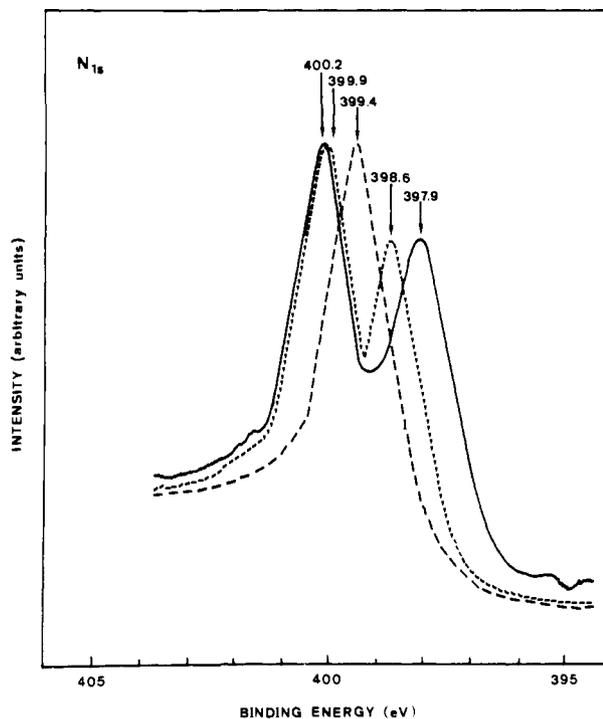


Figure 3. Comparison of the nitrogen 1s photoelectron spectra of H₂(Hemato-IX), —; *cis*-PtCl₂H₂(Hemato-IX), ---; and Pt(Hemato-IX), ···, using Mg Kα radiation. The binding energy scale was corrected assuming a C_{1s} binding energy of 285 eV.

drogen atoms are usually proposed. In the first type (1) the hydrogen atoms are bonded on opposite nitrogen atoms. The two protons are fixed to adjacent nitrogen atoms in the second type (2) and a bridged structure was proposed for the third type (3). Numerous physicochemical techniques used to solve this problem were not very conclusive.¹⁵ X-Ray structures of por-

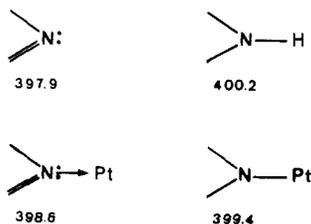
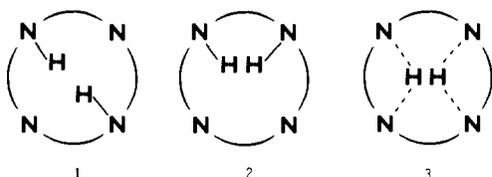


Figure 4. The N_{1s} binding energies (eV) found in H_2 (Hemato-IX), nitrogen aza type at 397.9 eV, nitrogen pyrrole type at 400.2 eV; in *cis*- $PtCl_2H_2$ (Hemato-IX), nitrogen aza type at 398.6 eV, nitrogen pyrrole type of 399.9 eV; in Pt (Hemato-IX), only one type at 399.4 eV.



phin,^{16,17} H_2 (TPP),^{17,18} H_2 (TPrP),^{17,19} (OEP),²⁰ and H_2 (Meso-IX-DME)²¹ indicated two N-H bonds diagonally situated. Moreover, ^{13}C and 1H NMR studied²²⁻²⁴ gave good evidence for a rapid N-H tautomerism in solution.

All the free-base porphyrins presented in Figures 1 and 5 have two N_{1s} peaks of equal intensity (Figures 6A and 6C, Table II) except for compound II (Figure 6B), which will be considered separately. The higher energy peak probably belongs to the pyrrole nitrogens and the lower energy peak to

Table II. N_{1s} Binding Energies (eV) of a Series of Porphyrins Referred to $C_{1s} = 285$ eV

	porphyrins	N_{1s}	$\Delta E_{N_{1s}}$	area ratios
I	H_2 (TPP)	400.3	1.8	1.0
		398.5		
II	H_2 (TPyP)	400.0	1.3	1.0
		398.7	2.1	2.0
		397.9		1.0
III	H_2 (Deut-IX-DME)	400.1	2.0	1.1
		398.1		
IV	H_2 (Proto-IX-DME)	400.0	1.8	1.0
		398.2		
V	H_2 (Copro-I-TME)	400.0	2.0	1.0
		398.0		
VI	H_2 (Copro-III-TME)	400.0	2.0	1.1
		398.0		

the aza nitrogens, this being due to the higher electronegativity of the pyrrole nitrogens. From Tables I and II these peaks are found for the free-base porphyrins around 400 and 398 eV. These results are in agreement with those obtained by Niwa et al.² and differ by less than 1 eV from others.^{1,3} This difference could be due to the use of two kinds of reference line, the carbon line (C_{1s}) for Niwa et al.² and our group, and the gold line, either $Au(4f_{5/2})^1$ or $Au(4f_{7/2})^4$, for the other groups. But the difference (ΔE) between the binding energies of the two types of nitrogen atoms is in all cases close to 2 eV. The binding energies reported in Tables I and II indicate no significant difference in the series of free-base porphyrins studied. The

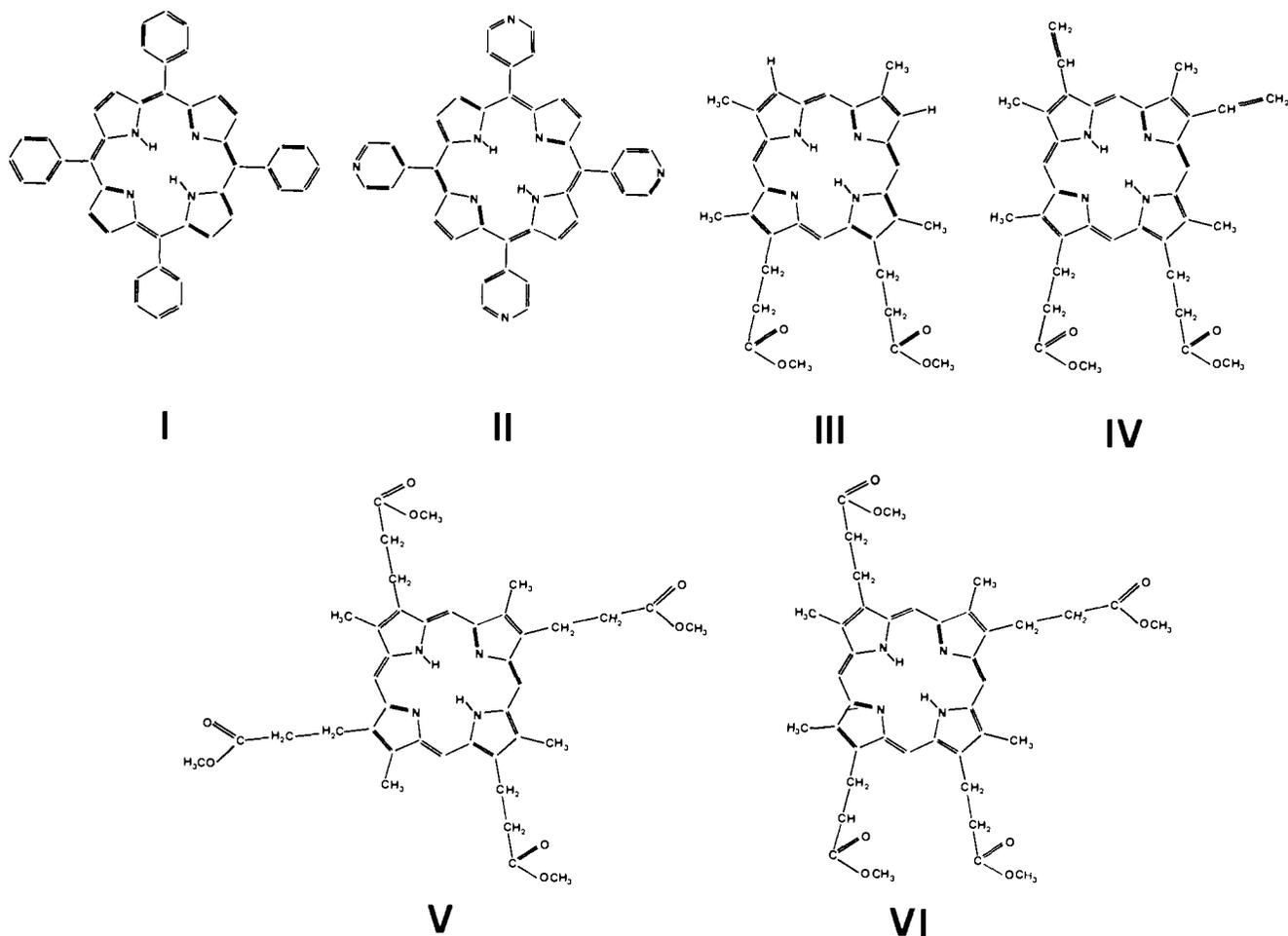


Figure 5. Structural representations of a series of porphyrin free bases used in the present work: I, H_2 (TPP); II, H_2 (TPyP); III, H_2 (Deut-IX-DME); IV, H_2 (Proto-IX-DME); V, H_2 (Copro-I-TME); and VI, H_2 (Copro-III-TME).

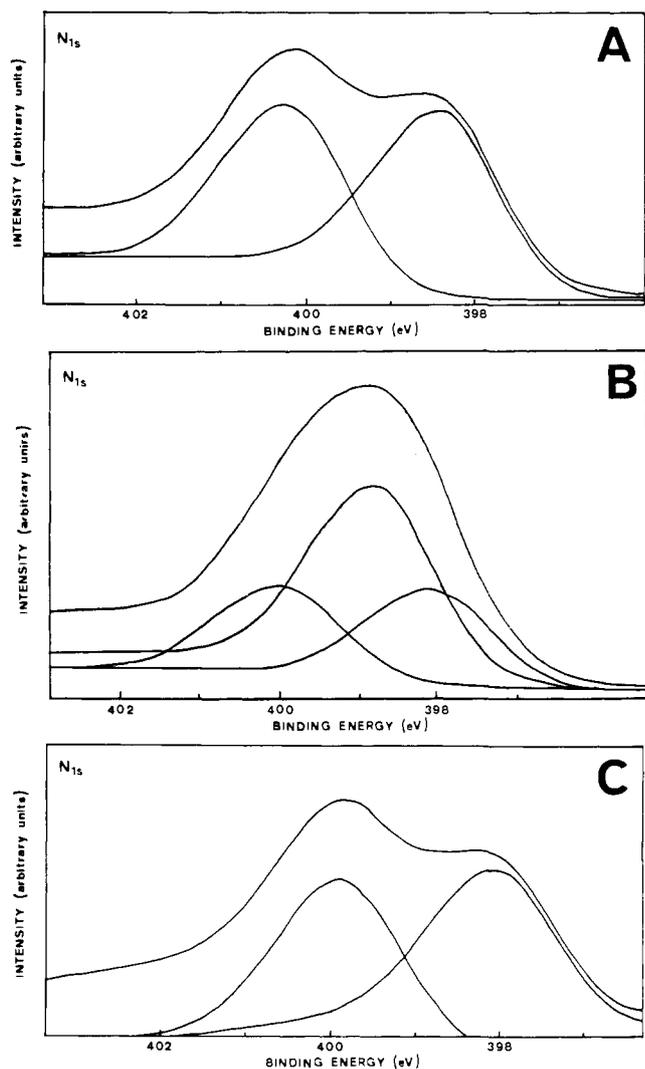


Figure 6. Nitrogen 1s and deconvolution spectra of (A) $H_2(TPP)$, (B) $H_2(TPyP)$, and (C) $H_2(Copro-III-TME)$ using Mg $K\alpha$ radiation. The binding energy scale was corrected assuming the lowest C_{1s} binding energy to be 285 eV.

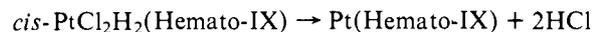
nature of the substituents at the periphery of the porphyrin molecule has no incidence on the N_{1s} core level in the present compounds.

One porphyrin needs more comment on its N_{1s} spectrum. $H_2(TPyP)$ has three types of nitrogen atoms, two aza, two pyrrole, and four nitrogen atoms from the pyridine rings found on the carbon meso. The nitrogen spectrum of this porphyrin is given in Figure 6B; only one broad band can be seen. A deconvolution spectrum gave three bands with area ratios of 1:2:1, one located at 400.0 eV, which probably corresponds to the two pyrrole nitrogens, the second one at 398.7 eV corresponding to the four pyridyl nitrogens, and the third one at 397.9 eV corresponding to the two aza nitrogens.

The reaction between $H_2(TPP)$ or $H_2(OEP)$ ¹⁰ and $[Rh(CO)_2Cl]_2$ gives an anionic species containing $[(CO)_2RhClRh(CO)_2]$, where each rhodium atom could be fixed on two adjacent nitrogen atoms. An N-methylated porphyrin like $H_2(NMeOEP)$ was found to bind $[(CO)_2RhCl_2Rh(CO)_2]$ where each Rh^I atom could be linked to one adjacent N atom.¹¹ This adduct forms $MeRh^{III}(OEP)$ upon heating with the methyl group bonded on Rh^{III} . The former adduct is an intermediate SAT²⁵⁻²⁷ complex. $H_2(Meso-IX-DME)$ reacting with $Tc_2(CO)_{10}$ gave $H(Meso-IX-DME)Tc(CO)_3$,²⁸ the rhenium complexes of $H_2(TPP)$ and $H_2(Meso-IX-DME)$ being also prepared by this way.²⁹ The proposed structure for

these compounds was a coordination of the rhenium atom on three nitrogen atoms. These adducts do not give rise to the corresponding metalloporphyrins upon heating.²⁸ The mononuclear dimetallic complexes of both technetium³⁰ and rhenium^{29,31} were also synthesized. An x-ray analysis³² has shown that the metal lies above and below the porphyrin plane.

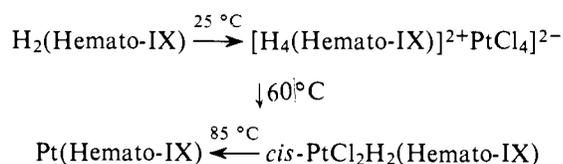
The SAT complex presented in this work has a new configuration never described or proposed. During the synthesis of the metalloporphyrin Pt(Hemato-IX), it has been possible to isolate an intermediate corresponding to the formula, $cis-PtCl_2H_2(Hemato-IX)$.⁸ The infrared spectrum shows the presence of N-H and it was possible to study, after isolation of this intermediate, the following reaction:⁸



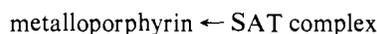
The Raman spectra of these porphyrins have recently been published.¹⁴ The present work is in complete agreement with the published data^{8,14} and interpretation of the results. XPS is able to differentiate the binding energies of aza nitrogens, aza nitrogens complexed with platinum, and nitrogen atoms where platinum is covalently bound. This is shown in Figure 4. In the SAT complex, the pyrrole nitrogens (399.9 eV) do not significantly differ from those of the free-base porphyrin (400.2 eV) but the aza nitrogens become more electronegative (396.6 eV in the SAT vs. 397.9 eV in the free base). We believe that a difference of 0.7 eV is significant. Moreover, the corresponding metalloporphyrin Pt(Hemato-IX) presents only one N_{1s} peak located at 399.4 eV indicating the existence of four equivalent nitrogens in this compound. The passage $H_2(Hemato-IX) \rightarrow cis-PtCl_2H_2(Hemato-IX) \rightarrow Pt(Hemato-IX)$ is represented in Figure 3. A difference of 0.8 eV between the N_{1s} binding energy of $N \rightarrow Pt$ in the SAT and N-Pt in the metalloporphyrin is real. To our knowledge, it is the first time that it is possible to differentiate between these two types of platinum binding. The binding energies for platinum in these complexes (Table I) are in agreement with the +2 oxidation state.³³ A value of 198.5 eV for the chlorine atoms in the SAT corresponds to the reported value for complexes containing $cis-PtCl_2$.³³ The cis configuration for the two chlorine atoms was also found with the infrared spectrum⁸ showing two ν_{Pt-Cl} at 332 and 323 cm^{-1} . It is interesting to mention that the visible spectra of the SAT in glacial acetic acid⁸ are similar to those reported for another SAT obtained between $H_2(TPP)$ and mercury(II) acetate, where two mercury atoms are bound with two adjacent nitrogen atoms,³⁴ one above and the other one below the plane of the porphyrin. The equivalency between the nitrogen atoms in the present series is becoming higher when the platinum atom is incorporated in the hematoporphyrin plane. Since the $cis-PtCl_2$ unit is complexed with $H_2(Hemato-IX)$, the problem is to know if the coordination takes place on two opposite or on two adjacent nitrogen atoms. The distance between two opposite nitrogen atoms in porphyrins is close to 4.1–4.2 Å.³⁵ The N-Pt distance in aminoplatinum complexes equals 2–2.1 Å, i.e., a distance of 3 Å between the two nitrogen atoms in the cis position. Based on the crystallographic considerations, a coordination of the platinum atom on two opposite nitrogen atoms is highly unlikely. But a distance of 2.8–2.9 Å between two adjacent nitrogen atoms in porphyrins is just the required length for a coordination with platinum. The proposed configuration for the SAT is given in Figure 1B. The platinum atom lies above the porphyrin plane. An approximate calculation based on a relation between the planarity of the porphyrin and the intensity of the 1588- cm^{-1} Raman band (which was found to be sensitive to the porphyrin deformations as demonstrated with the free base, the diacid species, the SAT complex, and the metalloporphyrin) indicates a deviation of the pyrrole rings of 18° from planarity in the SAT and a corresponding distance of 0.6 Å between platinum and the mean plane of the porphyrin.¹⁴

Consider now the different types of SAT models proposed (Figure 7). Fleischer considered the metal fixed on two opposite nitrogen atoms,⁶ whereas Hambright's model³⁶ has two metal atoms, one above and one below the porphyrin plane. In both cases, metals are fixed to the porphyrin with two M-N bonds. Tsutsui's models^{28,29} differ by the number of M-N bonds, three instead of two, and the two metal atoms are not on the S₂ axis as in the precedent cases. Takenaka et al.¹¹ reacted H(N-MeOEP) with [Rh(CO)₂Cl]₂ in benzene at room temperature and obtained a mononuclear dimetallic (N-MeOEP)[Rh^I(CO)₂Cl]₂ compound which, upon heating, gave the metalloporphyrin, MeRh^{III}(OEP). The same situation is encountered with the anionic intermediate [(OEP)-Rh^I(CO)₂Cl]⁻ which forms ClRh^{III}(OEP) upon heating.¹⁰ Another type of intermediate was also reported by Takenaka et al.³⁷ where the two Rh^I atoms have a square planar coordination above and below the porphyrin plane similar to the Re^I complex.³² X-Ray crystallography of this compound was recently reported³⁸ and indicated a tilting of the pyrrole rings from coplanarity with the mean plane of the porphyrin skeleton of 31.9°. It is interesting to compare this value with 33 and 28° obtained for the diacid species,²⁷ [H₄(TPP)]²⁺ and [H₄(TPyP)]²⁺. All of these rhodium porphyrins with the SAT configuration^{10,11,37-39} are the only compounds to our knowledge with the *cis*-PtCl₂H₂(Hemato-IX), which can be considered as intermediate since they can be transformed in the corresponding metalloporphyrin with the metal in the porphyrin plane.

We have been able to isolate and characterize in solution and in the solid state^{8,14} the following series:



The incorporation of platinum in H₂(Hemato-IX) proceeds via at least two steps which considerably deviate the porphyrin molecule from planarity. It is known that the metal incorporation in *N*-alkyl porphyrin is faster by 10⁵ compared with the free base,³¹ this being explained by the distortion of the porphyrin due to the *N*-alkylation.⁴⁰ *The deformation of the porphyrin seems to be one of the most important factors determining the metal incorporation.* It is interesting to mention that the two types of intermediate compounds (diacid species and SAT) isolated from H₂(Hemato-IX) and K₂[PtCl₄] were also obtained by two independent groups between H₂(OEP) and [Rh(CO)₂Cl]₂,^{37,41} i.e., the diacid species⁴¹ [H₄(OEP)]²⁺([Rh(CO)₂Cl₂]⁻)₂, which was found surprisingly to be planar, and the SAT³⁷ (OEP)[Rh(CO)₂]₂. The SAT complex can be transformed in the corresponding metalloporphyrin, but it would be worthwhile to know if the reaction [H₄(OEP)]²⁺([Rh(CO)₂Cl₂]⁻)₂ → (OEP)[Rh(CO)₂]₂ is possible. If this occurs we then dispose of two examples where the metal incorporation in a porphyrin follows the scheme



In conclusion, this work confirms the existence of a new type of SAT complex, an intermediate containing only one metal atom bonded on two adjacent aza-type nitrogen atoms. This compound has two very interesting "qualities": it is a hemato-porphyrin compound and also a *cis*-Pt complex. Hemato-porphyrin was shown to accumulate preferentially on tumors⁴² and the *cis*-Pt complexes are active against a wide variety of

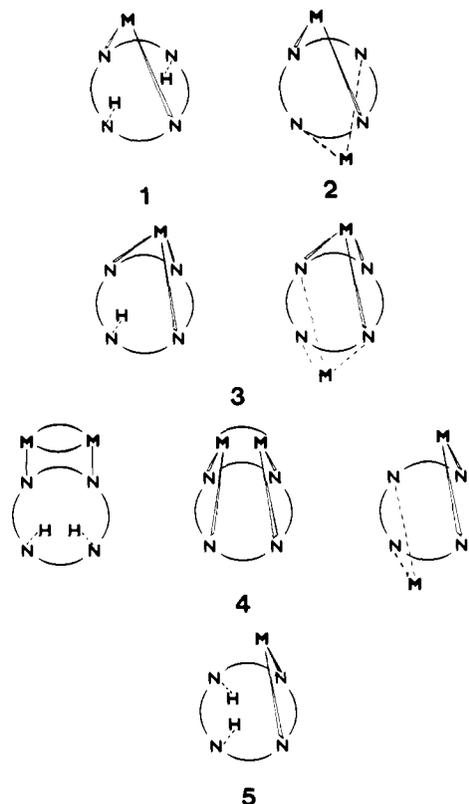


Figure 7. The different SAT models proposed by (1) Fleischer, (2) Hambright, (3) Tsutsui, (4) Yoshida and co-workers, and (5) Macquet and Theophanides.

tumors.⁴³ The anticancer activity of the SAT compound, *cis*-PtCl₂H₂(Hemato-IX), is now under investigation.

Abbreviations

H₂(Hemato-IX) = hemato-porphyrin IX free-base
 [H₄(Hemato-IX)]²⁺ = hemato-porphyrin IX diacid species
cis-PtCl₂H₂(Hemato-IX) = *cis*-dichloroplatinum(II) hemato-porphyrin IX
 Pt(Hemato-IX) = platinohemato-porphyrin IX
 H₂(TPP) = *meso*-tetraphenylporphyrin
 [H₄(TPP)]²⁺ = *meso*-tetraphenylporphyrin diacid species
 H₂(TPyP) = *meso*-tetra(4-pyridyl)porphyrin
 [H₄(TPyP)]²⁺ = *meso*-tetra(4-pyridyl)porphyrin diacid species
 H₂(Deut-IX-DME) = deuteroporphyrin IX dimethyl ester
 H₂(Proto-IX-DME) = protoporphyrin IX dimethyl ester
 H₂(Copro-I-TME) = coproporphyrin I tetramethyl ester
 H₂(Copro-III-TME) = coproporphyrin III tetramethyl ester
 H₂(TPPrP) = *meso*-tetra(*n*-propyl)porphyrin
 H₂(OEP) = octaethylporphyrin
 H₂(*meso*-IX-DME) = mesoporphyrin IX dimethyl ester
 SAT = sitting-atop
 NMR = nuclear magnetic resonance
 XPS = x-ray photoelectron spectroscopy

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Kinetics of Alkali Metal Complex Formation with Cryptands in Methanol

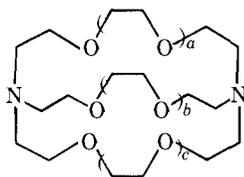
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Abstract: The rates of dissociation of a variety of alkali metal cryptates have been measured in methanol. These have been combined with measured stability constants to give the corresponding formation rates. The pronounced selectivity of the cryptands for alkali metal cations is found to be reflected entirely in the dissociation rates, with the formation rates increasing monotonically with increasing cation size. The specific size-dependent interactions between the metal ions and the cryptands must then occur subsequent to the formation of the transition state (in the formation reaction). For a given metal ion, the formation rates increase with increasing cryptand size, and for 2,2,2 are similar to the rates of solvent exchange in the inner sphere of the cations. This suggests that during complex formation, particularly for the larger cryptands, interactions between the cryptand and the incoming cation can compensate very effectively for the loss of solvation of the cations.

Introduction

The pronounced selectivity of the macrobicyclic cryptands² (1–3) for alkali metal cations, and the dependence of the se-



- 1, $a = 1$; $b = c = 0$ (2,1,1)
 2, $a = b = 1$; $c = 0$ (2,2,1)
 3, $a = b = c = 1$ (2,2,2)

lectivity pattern on the ligand size, provide the opportunity for a systematic study of factors influencing the kinetics and thermodynamics of complex formation involving alkali metal cations. Such information is of particular relevance to current studies concerning the mechanism of action of a variety of naturally occurring macrocyclic and open-chain antibiotics.

These species show marked selectivity in the stability constants for complex formation with cations, and in the transport of cations through natural and artificial membranes.^{3,4}

Several kinetic studies of complex formation between cryptands and alkali metal ions^{5–9} and alkaline earth ions^{6,10} in water have been published. Where appropriate comparisons can be made, the results suggest that the dissociation rates vary more from one system to another than the association rates.^{2,5,6,10} However, the relatively low stability of the complexes in water (except for complexes corresponding to, or near to, the optimal fit of the cation into the intramolecular cavity of the ligand) makes a study over a wide range of complexes difficult. In methanol, however, the stability constants are several orders of magnitude larger than those in water,¹¹ permitting a more systematic investigation of complex formation.

In the present paper we present the results of a study of the kinetics and thermodynamics of complex formation in methanol between the cryptands 1–3 and alkali metal cations. The dissociation rates in methanol are slower than the corre-