Interaction between Porphyrins and Hydroxylated Compounds. Part 2.[1] Effect of *p*-Nitrophenol during the Metallation of Tetraphenylporphyrin

Laure Guilleux, Pierre Krausz, Louis Nadjo, and Raoul Uzan*
Université d'Amiens, Laboratoire de Chimie Organique Physique, 33 rue Saint-Leu, 80039 Amiens Cedex, France

The behaviour of tetraphenylporphyrin during its metallation with copper(II) acetylacetonate has been investigated in the presence of *p*-nitrophenol in benzene and in dichloromethane. Rate constants have been measured, and the forward reaction has been shown to be catalysed by *p*-nitrophenol. The kinetic orders of reaction were 1, 1, and 0.5 in porphyrin, *p*-nitrophenol, and Cu(acac)$_2$ respectively in both solvents. Moreover, in CH$_2$Cl$_2$ a dimeric form of Cu(acac)$_2$ was observed; only the monomeric species reacts with the porphyrin. A general mechanism is proposed.

The insertion of a metal into a free-base porphyrin has been the subject of numerous controversial papers, but no definitive mechanism has yet been proposed. However, in all cases some difficulty in inserting the metal, especially in aprotic solvents,[1] has been observed. Some authors assert that metal insertion is facilitated by the flexibility of the macrocyclic skeleton.[2] Lavallee *et al.*[3] have shown that with an *N*-methylporphyrin, which is permanently distorted, metallation is greatly enhanced.

The aim of the present paper is to show how a non-permanent distortion of a porphyrinic macrocycle, induced by a *p*-nitrophenol ligand, can accelerate metal insertion. In a preceding paper[4] we have shown that tetraphenylporphyrin (P) can be complexed by *p*-nitrophenol (L), giving a monocomplexed (PL), then a dicomplexed porphyrin (PL$_2$), or, with a solvent of sufficiently high dielectric constant, a second-order aggregate (P$_2$L$_2$). All these complexes are formed through intermolecular hydrogen bonds between nitrogen or oxygen atoms and hydrogen atoms.

$$\begin{tikzcd} & \mathrm{PL_2} \arrow[d, shift left] \\ \mathrm{P} + \mathrm{L} \arrow[r, shift left] & \mathrm{PL} \arrow[l, shift left] \arrow[u, shift left, "\mathrm{L}"] \arrow[d, shift left, "\mathrm{PL}"] \\ & \mathrm{P_2L_2} \arrow[u, shift left] \end{tikzcd} \qquad (1)$$

To explain the subsequent changes to PL, we have hypothesized that the monocomplexation of tetraphenylporphyrin free base, which is known for its flexibility,[5] induces a transitory distortion, making the remaining nitrogen atoms more available. We have also taken advantage of the ability of hydroxylated compounds like *p*-nitrophenol to accelerate copper insertion to study the mechanism of this reaction.

Results

The kinetics of insertion of Cu^{2+} into P in the presence of L were studied first. The copper was introduced as its acetylacetonate Cu(acac)$_2$. This reactant is soluble in aprotic medium and, more importantly, dissociates to give the very weakly acidic acetylacetone. Moreover, it is able readily to insert metal into porphyrins.[6]

Table 1. Variation of the pseudo-first-order rate constant as a function of the concentrations of *p*-nitrophenol and copper(II) acetylacetonate, in benzene

10^3 [L]/mol l^{-1}	10^4 [Cu(acac)$_2$]$_0$/mol l^{-1}	$10^4 k_i$/s^{-1}
2.6	9.63	10.66
2.6	2.41	5.23
2.6	0.96	3.35
3.54	9.66	13.38
2.83	9.66	10.35
2.48	9.66	8.25

Table 2. Variation of the pseudo-first-order rate constant as a function of *p*-nitrophenol and copper(II) acetylacetonate, in dichloromethane

10^3 [L]/mol l^{-1}	10^5 [Cu(acac)$_2$]$_0$/mol l^{-1}	$10^4 k_i$/s^{-1}
1.078	95.78	3.91
3.23	95.78	19.29
5.39	95.78	27.55
6.47	95.78	31.45
3.08	2.90	2.74
3.08	3.86	2.94
3.08	7.88	4.09

(a) *Kinetic Study of the System* P–L–Cu(acac)$_2$ *in Benzene.*—In benzene, with the respective concentrations of P, L, and Cu(acac)$_2$ roughly 10^{-6}, 10^{-3}, and 10^{-3} mol l^{-1}, initial kinetic orders of 1, 1, and 0.5 were obtained, respectively. During the first 100 s of reaction the same kinetic orders were observed by studying the variation of $r = (A_\infty - A_t)/(A_\infty - A_0)$,† which is directly proportional to the porphyrin concentration. With concentrations of L and Cu(acac)$_2$ in excess of that of P, the change of absorbance reflects only changes in the porphyrin, because the total copper salt concentration remains essentially constant throughout the metallation. The apparent initial rate constants k_i are determined exactly by the slope of the straight line ln r = f(t) (Table 1). The real rate constant k could then be deduced from the relationship (2) (Figure 1), and a value of (12 ± 3) l$^{\frac{3}{2}}$ mol$^{-\frac{3}{2}}$ s^{-1} was found.

$$k_i = k\,[\mathrm{L}]_0\,[\mathrm{Cu(acac)_2}]_0^{0.5} \qquad (2)$$

(b) *Kinetic Study of the System* P–L–Cu(acac)$_2$ *in Dichloromethane.*—In dichloromethane (dielectric constant D = 9.08, much larger than that of benzene), under the same conditions, the same reaction orders were observed for P and L. However no simple order was obtained for the metallic salt (Figure 2). These results prove that Cu(acac)$_2$ self-associates (see

---

† A_0, A_∞, and A_t are respectively the optical densities at the beginning and the end of the reaction, and after time t.

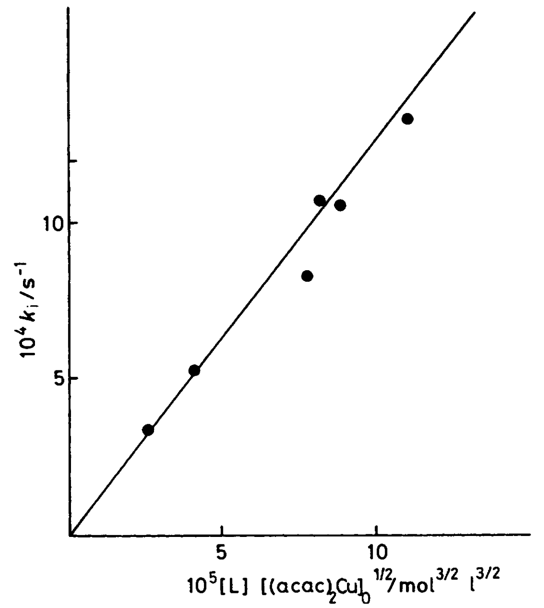


Figure 1. Determination of apparent first-order rate constant in C_6H_6 (for notation see text)

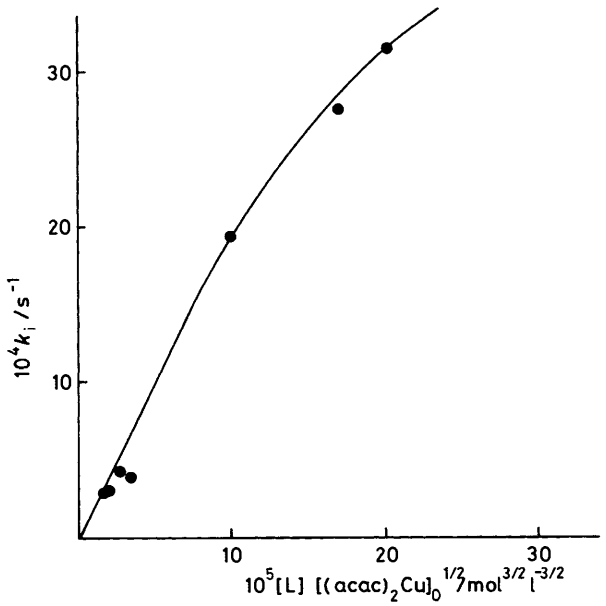


Figure 2. Plot of k_i *vs.* $[Cu(acac)_2]_0^{0.5}$ [L] in CH_2Cl_2 (for notation see text)

$$2\,Cu(acac)_2 \xrightleftharpoons{K_1} Cu_2(acac)_4 \qquad (3)$$

where $K_1 = [Cu_2(acac)_4]/[Cu(acac)_2]^2$

$$k_i = k\,[L]_0\,[Cu(acac)_2]_m^{0.5} \qquad (4)$$

Appendix). The modified relationship (2) is then (4), where $[Cu(acac)_2]_m$, the concentration of monomeric acetylacetonate, is related to the initial analytical concentration $[Cu(acac)_2]_0$ by the classical equation (5). Experimental results give k_i = (27 ± 3) l$^{\frac{3}{2}}$ mol$^{-\frac{3}{2}}$ s^{-1}.

$$[Cu(acac)_2]_m = \{-1 + (1 + 8K_1\,[Cu(acac)_2]_0)^{\frac{1}{2}}\}/4K_1 \qquad (5)$$

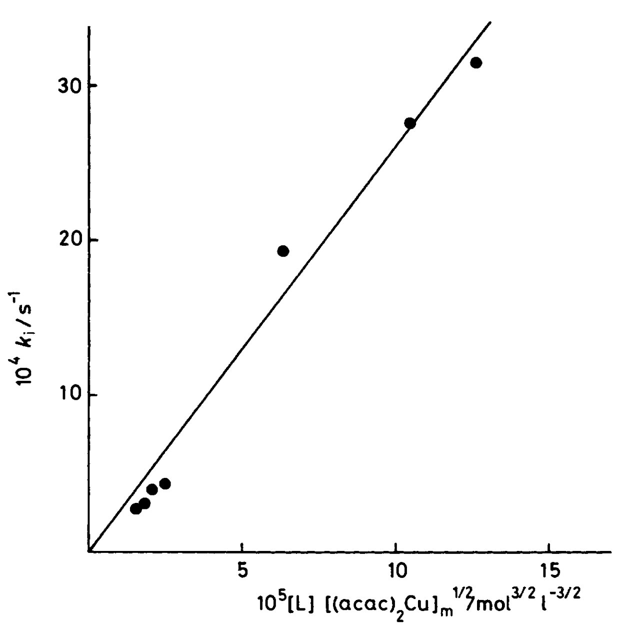


Figure 3. Determination of apparent first-order rate constant in CH_2Cl_2 (for notation see text)

(c) *Comparison with Results in the Absence of* L.—In the absence of L, in benzene as well as in dichloromethane, the reaction is roughly 1000 times slower, showing the 'catalytic activity' of the hydroxylated compound.

Discussion

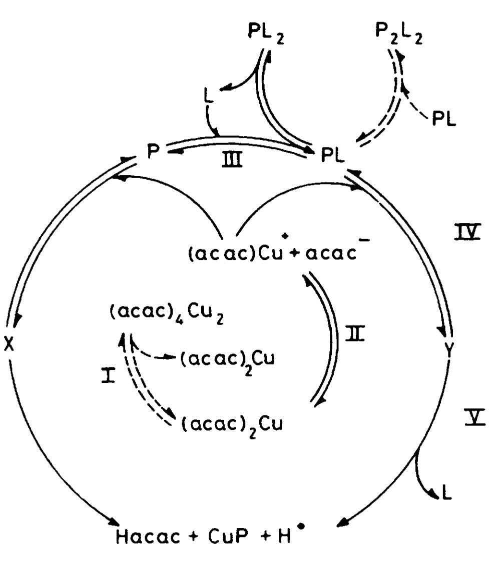
From comparative analysis of literature results, it appears that very different conclusions are reached regarding the kinetics of insertion of a divalent metal into a porphyrin, depending on the conditions (solvent, catalyst, metallic salt, porphyrin, *etc.*).[1] By analogy with results in the insertion of metals using other metal salts, like acetates,[7] the insertion in the present case must be effected from monomeric copper(II) acetylacetonate and not from the dimeric form. The kinetic order of 0.5 can be interpreted in terms of a fast dissociation equilibrium (6). This

$$Cu(acac)_2 \xrightleftharpoons{K_{II}} Cu(acac)^+ + acac^- \qquad (6)$$

where $K_{II} = [Cu(acac)^+][acac^-]/[Cu(acac)_2]$

equilibrium has already been observed in aprotic medium.[8] The complete inhibition of insertion together with the non-observance of the diprotonated form of P in the presence of an excess of acetylacetone further supports the existence of this equilibrium.

As the role of L in this process is catalytic, a complex between the porphyrin and the hydroxylated substrate must be formed. We have shown that such a complex is formed through intermolecular hydrogen bonds (shifting towards ion pairs) between the proton of the pyrrole nitrogen and the phenolic oxygen on one hand, and between the lone pair on the pyrrole nitrogen and the hydroxylic proton on the other. Such a process leads to the formation of mono- (PL) and di-complexed (PL_2) entities. Without excluding the intervention of PL_2 in the metallation process, it is reasonable to consider that, as a consequence of the distortion of the macrocycle and the resulting increased availability of the nitrogen atoms, it is the mono-complex PL which reacts with the cationic form of the metallic salt. We have confirmed by u.v. and i.r. spectroscopy that there is no association between L and the metallic salt or between L and the copper(II) tetraphenylporphyrinate. Lastly,



Scheme.

no inhibition of the insertion process is observed upon addition of an excess of $Cu^{II}P$, showing that the metallation of the porphyrin is irreversible. On the basis of the preceding results, we tentatively propose the mechanistic scheme shown, where X and Y represent $[(acac)CuHPH]^+$ and $[(acac)CuHPH \ldots L]^+$, respectively.

Preceding results[1] have clearly demonstrated that in such a process the rate-determining step is the metallation reaction. We have postulated that the equilibria I, II, and III are reached instantaneously [equations (7)—(9)], and we have applied the

$$K_{I} = [Cu_2(acac)_4]/[Cu(acac)_2]^2 \qquad (7)$$

$$K_{II} = [Cu^+(acac)]^2/[Cu(acac)_2] \qquad (8)$$

$$K_{III} = [PL]/[P][L] \qquad (9)$$

quasi-stationary-state approximation [equation (10)]. The kinetic analysis of the reaction scheme in the presence of L leads to the relationship (11), with k_4 and k_{-4} the forward and

$$-\frac{d[Y]}{dt} = 0 = k_5[Y] + k_{-4}[Y] - k_4[PL][(acac)Cu^+]$$
$$= k_4[Y] + k_{-4}[Y] - k_4K_{III}[P][L][(acac)Cu^+] \qquad (10)$$

$$-\frac{d[P]}{dt} = \frac{d[CuP]}{dt} = \frac{k_5k_4}{k_5 + k_{-4}} K_{III}K_{II}^{0.5}[Cu(acac)_2]_m^{0.5}[P][L] \qquad (11)$$

backward rate constants of step IV, and k_5 the rate constant of step V. The good agreement between the calculated kinetic reaction orders and the experimental results strongly supports this scheme, wherein the experimental rate constant is identical with $[k_5k_4/(k_5 + k_{-4})]\ K_{III}K_{II}^{0.5}$. The factor of 2.5 difference between the initial rate constants in benzene and in dichloromethane can be ascribed in particular to a larger dissociation equilibrium constant K_{II} in dichloromethane, due to the difference in dielectric constants. Besides the fundamental interest of the present kinetic study as evidence of the distortion of the macrocycle during complexation of the free base by hydroxylated entities, we believe that we have established a method for fast metallation of P. By the same technique, other divalent metals have been inserted (*e.g.* Zn^{II} and Co^{II}). The method can also be applied to other metals with various oxidation states. Thus, we have obtained, for the first time, under mild conditions, from indium acetylacetonate, the complex *p*-nitrophenolato(tetraphenylporphyrinato)indium(III) ($\lambda_{max.}$ 425, 521, and 558 nm) in 3 min with a yield higher than 90% at 23 °C.

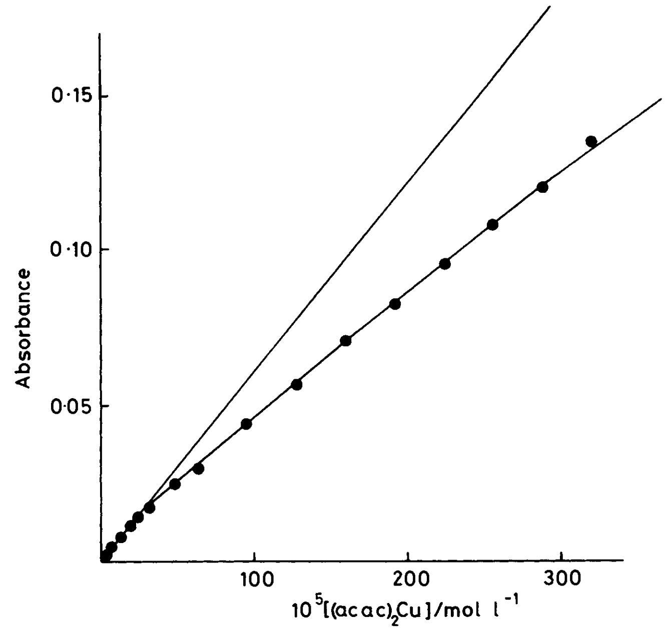


Figure 4. Concentration dependence of the absorbance of $Cu(acac)_2$ in dichloromethane solution, the straight line shows the Beer law behaviour at 537 nm (ε = 61); the circles represent the experimental data and the line passing through the points the theoretical graph

Experimental

(1) *Reactants and Solvents.*—The reactants P and L and the solvents were purified as described previously.[4] The acetylacetonates were all commercial products (ROC/RIC). Acetylacetone (Aldrich) was purified by g.l.c.

(2) *Representative Kinetic Experiment.*—Kinetic experiments were performed at fixed wavelength (usually 537 nm) with a Varian Cary 219 spectrophotometer. The quartz cells had 10 mm optical path and were carefully degassed with dry argon. The solution of P and L was then introduced and maintained at constant temperature (23 ± 1 °C). The metallic salt solution was then introduced and the spectrum immediately recorded. We confirmed that the kinetic results were independent of the order of introduction of reactants.

(3) *I.r. Spectra.*—I.r. spectra were recorded with a Perkin-Elmer 281 instrument with a KBr cell of 0.1 mm optical path.

Appendix

Self-association of Copper(II) *Acetylacetonate.*—As deduced from the kinetic analysis of the experimental results, the dimeric entities do not participate in the metallation of free-base porphyrins and the self-association of the metallating agent will play an important role in the insertion kinetics. When the variations of absorbance of copper acetylacetonate at 537 nm were followed as a function of the introduced salt concentration, no deviation from Beer's law was observed in benzene; thus any self-association of copper(II) acetylacetonate in this solvent was excluded up to a concentration of 10^{-2} mol l^{-1}. However, in dichloromethane, with a higher dielectric constant, a clear deviation from Beer's law was observed from a concentration of roughly 10^{-3} l^{-1} (Figure 4) of acetylacetonate. Using the method described previously[4] and comparing experimental and theoretical curves from the relationship (12) (notation as in ref.

$$\Delta A = \Delta\varepsilon\,\{4K_1[\mathrm{Cu(acac)_2}]_0 + 1 - (1 + 8K_1[\mathrm{Cu(acac)_2}]_0)^{\frac{1}{2}}\}/4K_1 \quad (12)$$

4), it is seen that the deviation is related to a second-order self-association (Figure 4) with the value of the equilibrium constant $K_1 = 2\,130$ l mol^{-1}.

References

1 For a recent review see F. R. Longo, E. M. Brown, W. G. Rau, and A. D. Adler in 'The Porphyrins,' ed. D. Dolphin, Academic Press, New York, 1978, ch. 10, p. 458.

2 (*a*) D. A. Buckingham, C. R. Clark, and W. S. Webley, *J. Chem. Soc., Chem. Commun.*, 1981, 192; (*b*) P. Hambright and P. B. Chock, *J. Am. Chem. Soc.*, 1974, **96**, 3123.

3 (*a*) D. K. Lavallee and O. P. Anderson, *J. Am. Chem. Soc.*, 1982, **104**, 4707; (*b*) M. J. Bain-Ackerman and D. K. Lavallee, *Inorg. Chem.*, 1979, **18**, 3358.

4 L. Guilleux, P. Krausz, L. Nadjo, R. Uzan, and Ch. Giannotti, *J. Chem. Soc., Perkin Trans. 2*, 1984, 475.

5 A. Stone and E. B. Fleisher, *J. Am. Chem. Soc.*, 1968, **90**, 2735.

6 J. W. Buchler, G. Eikelmann, L. Puppe, K. Rohbock, H. H. Schneehage, and D. Weck, *Justus Liebigs Ann. Chem.*, 1971, **745**, 135.

7 J. James and P. Hambright, *Inorg. Chem.*, 1973, **12**, 474.

8 E. Bialkowska, K. Leibler, and M. K. Kalinowski, *Monatsh. Chem.*, 1976, **107**, 865.

Received 17*th July* 1984; *Paper* 4/1234