Inorg. Chem. **1984**, *23*, 2249–2251

Contribution from the Laboratory of Analytical Chemistry,
Faculty of Science, Nagoya University, Chikusa-ku, Nagoya 464, Japan

High-Pressure Stopped-Flow Studies on the Metalation of *N*-Methyl-5,10,15,20-tetraphenylporphine in *N*,*N*-Dimethylformamide

SHIGENOBU FUNAHASHI, YŪSHI YAMAGUCHI, and MOTOHARU TANAKA*

Received August 30, 1983

The kinetics of incorporation of metal ions (Mn(II), Co(II), Ni(II), Zn(II), Cd(II), Hg(II)) into *N*-methyl-5,10,15,20-tetraphenylporphine was studied spectrophotometrically in *N*,*N*-dimethylformamide by using a high-pressure stopped-flow technique. The rate is first order in metal ion and porphyrin, and the values of activation volume (ΔV^{*}, cm^3 mol^{-1}) for the metalation are as follows: 12.9 ± 0.8 for Mn^{2+}; 8.0 ± 0.3 for Co^{2+}; 9.0 ± 0.9 for Ni^{2+}; 7.0 ± 0.6 for Zn^{2+}; 8.9 ± 1.6 for Cd^{2+}; 4.3 ± 0.8 for Hg^{2+}. The positive activation volume strongly indicates a dissociative character of the activation process.

Introduction

Recently we have studied the kinetics of reactions of 5,10,15,20-tetraphenylporphine (H_2(TPP)) and *N*-methyl-5,10,15,20-tetraphenylporphine (H(MeTPP)) with copper(II), zinc(II), and cadmium(II) ions in *N*,*N*-dimethylformamide (DMF) at 25 °C and pointed out the mechanistic difference in the metalation of these two porphyrins.[1] Bain-Ackerman and Lavallee[2] have performed the kinetic study for the complexation of H(MeTPP) by Mn(II), Co(II), Ni(II), Cu(II), and Zn(II) ions in DMF and have pointed out the importance of porphyrin deformation to the rate and a dissociative interchange mechanism. Although a number of kinetic studies on metalloporphyrin formation in solution have been focused on the mode of metal ion incorporation into porphyrin nucleus,[3–6] there seems to be no mechanistic approach on the basis of the activation volumes.

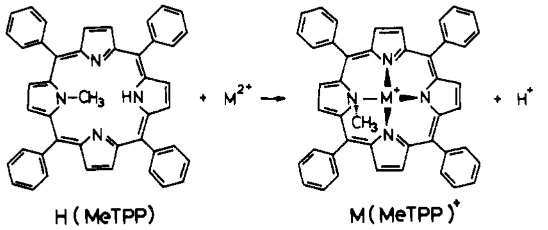
We have recently constructed a high-pressure stopped-flow apparatus,[7] which enables us to follow reactions under pressures up to 200 MPa. In the present paper, rates of incorporation of metal ions (Mn^{2+}, Co^{2+}, Ni^{2+}, Zn^{2+}, Cd^{2+}, Hg^{2+}) into H(MeTPP) in DMF have been measured by using this apparatus. This paper seems to be the first high-pressure study on the formation of metalloporphyrins.[8]

Experimental Section

Materials. H(MeTPP) was prepared by methylation of H_2(TPP) with methyl fluorosulfate (Aldrich Chemical Co.) according to the literature procedures.[9] H(MeTPP) was isolated and purified by a thin-layer chromatograph. H(MeTPP) is characterized by electronic spectra and by the distinctive NMR spectrum, which shows a sharp singlet due to *N*-methyl group at 4.1 ppm upfield from $SiMe_4$ in $CDCl_3$. Reagent grade DMF was dried over 3A molecular sieves and distilled twice under reduced pressure.

Reagent grade metal(II) nitrates were recrystallized twice from distilled water. Crystals of the hydrated metal(II) nitrate salts were dissolved in DMF. The water in the DMF solution was removed by 3A molecular sieves under vacuum line. Then, the molecular sieves were removed by filtration. The amounts of water remaining in the DMF sample solutions were determined to be less than 5 × 10^{-3} mol dm^{-3}. The concentrations of metal(II) ion (Ca^{2+}, Mn^{2+}, Co^{2+}, Ni^{2+}, Zn^{2+}, Cd^{2+}, Hg^{2+}) solutions were determined complexometrically by using a standard EDTA solution. The purified DMF and the metal DMF solutions were prepared fresh just before kinetic measurements.

Scheme I



Measurements. The reaction was started by mixing a metal(II) nitrate solution and a H(MeTPP) solution. The reactions for all reaction systems studied at atmospheric pressure and at various temperatures were monitored spectrophotometrically by using a highly sensitive spectrophotometer (Type SM401, Union Giken, Osaka, Japan). All absorption spectra for metalloporphyrin formation as a function of time have several clear isosbestic points. It should be noted that a second reaction, demethylation,[10,11] which results in a nonmethylated porphyrin, can also take place while the first reaction, metalation, is progressing. Each reaction can be characterized by its own set of isosbestic points. Thus, kinetic data were collected for as long as the first set of isosbestic points was maintained. The reactions studied are given in Scheme I. Reaction runs under various pressures up to 200 MPa were followed at constant wavelength by a high-pressure stopped-flow apparatus with spectrophotometric detection (Type FIT 3).[7,12]

Rates were measured under pseudo-first-order conditions, i.e., in large excess of metal ion concentrations over the porphyrin concentration. The H(MeTPP) concentration was generally (0.5–1) × 10^{-5} mol dm^{-3}, and the metal concentration range was 5 × 10^{-5} to 5 × 10^{-2} mol dm^{-3}. Pseudo-first-order plots showed good linearity, and conditional first-order rate constants $k_{0(\mathrm{M})}$ were obtained from the slopes of such plots. The rate constants for nickel(II) and manganese(II) ions were determined by the Guggenheim method, which does not require a final absorbance value. Calcium(II) nitrate was used to maintain the ionic strength.

Results and Discussion

The rates of reactions of H(MeTPP) with a large excess of metal ion were studied in DMF solution containing a large amount of calcium(II) nitrate. Conditional first-order rate constants $k_{0(\mathrm{M})}$ obtained under the pseudo-first-order conditions are proportional to metal(II) ion concentration over a wide range (see Figure 1). Thus, in all cases the metalloporphyrin formation was found to be first order with respect to porphyrin and metal ion. The rate is given by eq 1, where k represents

$$d[\mathrm{M(MeTPP)}^{+}]/dt = k[\mathrm{H(MeTPP)}][\mathrm{M}^{2+}] \qquad (1)$$

the second-order rate constant. The temperature dependence

---

(1) Funahashi, S.; Yamaguchi, Y.; Tanaka, M. *Bull. Chem. Soc. Jpn.* **1984**, *57*, 204.

(2) Bain-Ackerman, M. J.; Lavallee, D. K. *Inorg. Chem.* **1979**, *18*, 3358.

(3) Scheider, W. *Struct. Bonding (Berlin)* **1975**, *23*, 123.

(4) Hambright, P. "Porphyrins and Metalloporphyrins"; Smith, K. M., Ed.; Elsevier: New York, 1975; Chapter 6.

(5) Longo, F. R.; Brown, E. M.; Rau, W. G.; Adler, A. D. "The Porphyrins"; Dolphin, D., Ed.; Academic Press: New York, 1978; Vol. V, Chapter 10.

(6) Tanaka, M. *Pure Appl. Chem.* **1983**, *55*, 151.

(7) Ishihara, K.; Funahashi, S.; Tanaka, M. *Rev. Sci. Instrum.* **1982**, *53*, 1231.

(8) A preliminary communication describes the results for the Co^{2+}–H(MeTPP) system: Funahashi, S.; Yamaguchi, Y.; Tanaka, M. *J. Chem. Soc., Chem. Commun.* **1982**, 976.

(9) Lavallee, D. K.; Gebala, A. E. *Inorg. Chem.* **1974**, *13*, 2004.

(10) Lavallee, D. K. *Inorg. Chem.* **1976**, *15*, 691.

(11) Lavallee, D. K. *Inorg. Chem.* **1977**, *16*, 955.

(12) Ishihara, K.; Funahashi, S.; Tanaka, M. *Inorg. Chem.* **1983**, *22*, 2564.

0020-1669/84/1323-2249$01.50/0

Table I. Rate Constants and Activation Parameters for Metalloporphyrin Formation and Solvent Exchange of Metal(II) Ions in DMF

	metalloporphyrin formation of H(MeTPP)					DMF exchange on metal(II) ions					
M(II)	k(25 °C)/ $\mathrm{mol^{-1}\,dm^3\,s^{-1}}$	$\Delta H^\ddagger$/ $\mathrm{kJ\,mol^{-1}}$	$\Delta S^\ddagger$/ $\mathrm{J\,K^{-1}\,mol^{-1}}$	$\Delta V^\ddagger$/ $\mathrm{cm^3\,mol^{-1}}$	ref	k_{ex}(25 °C)/ $\mathrm{s^{-1}}$	$\Delta H^\ddagger$/ $\mathrm{kJ\,mol^{-1}}$	$\Delta S^\ddagger$/ $\mathrm{J\,K^{-1}\,mol^{-1}}$	$\Delta V_{ex}^\ddagger$/ $\mathrm{cm^3\,mol^{-1}}$	ref	$\log (k_{ex}/k)$
Mn(II)	0.14 ± 0.01	78.6 ± 0.5	2.5 ± 1.6	12.9 ± 0.8	*a*	2.4×10^6	37	3		b	7.23
	0.010 ± 0.002	90 ± 2	19 ± 7		*c*						
Co(II)	0.38 ± 0.3[d]	71.6 ± 1.4[d]	−12 ± 5[d]	8.0 ± 0.3	*a*	3.9×10^5	57 ± 2	53 ± 9	6.7 ± 0.3	*e, f*	6.00
	0.68 ± 0.04	85 ± 5	35 ± 15		*c*						
Ni(II)	$(6.3 \pm 2.0) \times 10^{-3}$	91 ± 7	16 ± 23	9.0 ± 0.9	*a*	3.8×10^3	63 ± 2	33 ± 9	9.1 ± 0.3	*e, f*	5.78
	3×10^{-4}	90 ± 9	−13 ± 24		*c*						
Zn(II)	11.5 ± 0.3[g]			7.0 ± 0.6	*a*	5.6×10^6 [h]					5.69
	10.4 ± 0.8	59 ± 3	−28 ± 11								
Cd(II)	$(5.8 \pm 1.0) \times 10^2$ [g]	54 ± 3	−13 ± 9	8.9 ± 1.6	*a*	6.5×10^7	23 ± 5	−19 ± 17		*i*	5.04
Hg(II)	$(7.3 \pm 3) \times 10^5$	23 ± 3	−59 ± 9	4.3 ± 0.8	*a*	5×10^8 [h]					2.84

[a] This work; present determinations done with metal nitrate salts. [b] Chen, T.-M.; Morgan, L. O. *J. Phys. Chem.* **1972**, *76*, 1973. [c] Reference 2; determinations in ref 2 done with metal perchlorate salts. [d] Reference 8. [e] Matwiyoff, N. A. *Inorg. Chem.* **1966**, *5*, 788. [f] Reference 15. [g] Reference 1. [h] The DMF exchange rate is not available and estimated from the linear relationship of log k_{ex}(DMF) with log $k_{ex}(H_2O)$: Burgess, J. "Metal Ions in Solution"; Horwood: Sussex, England, 1978; Chapter 11. [i] Yamada, S.; Verrall, R. E. *J. Phys. Chem.* **1981**, *85*, 3145.

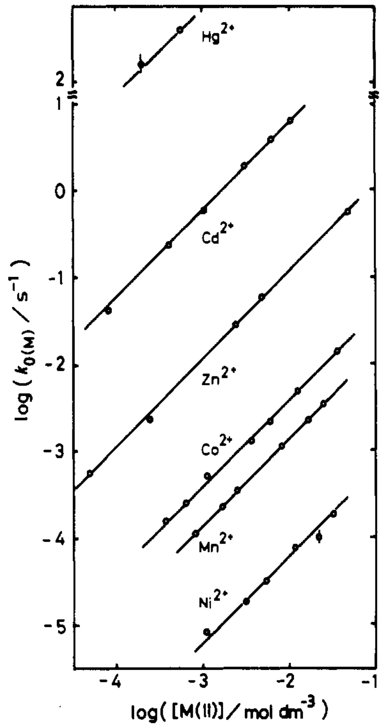


Figure 1. Dependence of first-order rate constant $k_{0(M)}$ on the metal(II) ion concentration [M(II)]. Solid lines represent the straight lines with the slope of unity, and the circles are the averages of several determinations. The rate constants for Zn(II) and Cd(II) ions are given in ref 1.

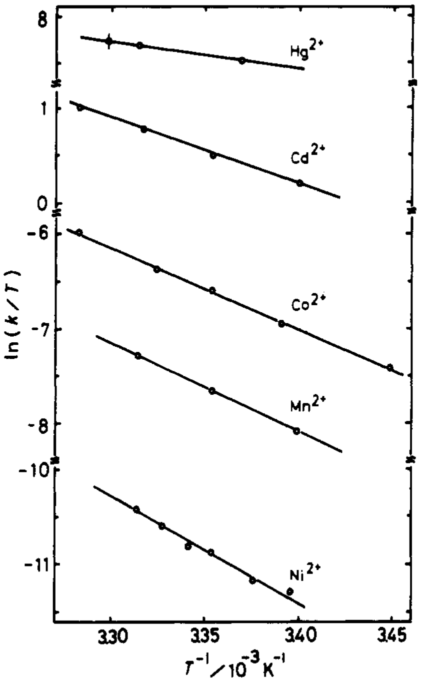


Figure 2. Temperature dependence of second-order rate constants. k is given in $\mathrm{mol^{-1}\,dm^3\,s^{-1}}$. The solid line represents a least-squares fit.

of k is given in Figure 2 according to the Eyring plot. Values of enthalpy and entropy of activation ($\Delta H^\ddagger$ and $\Delta S^\ddagger$) are summarized in Table I. According to the transition-state theory, the change in rate constant with pressure is given by $(\partial \ln k/\partial P)_T = -\Delta V^\ddagger/RT$, where $\Delta V^\ddagger$ is the activation volume. In Figure 3, logarithmic values of rate constant k are plotted against pressure. The linear plot thus obtained clearly indicates the pressure independence of $\Delta V^\ddagger$. The $\Delta V^\ddagger$ values obtained are tabulated in Table I. In Figures 1–3, the solid lines represent a least-squares fit and the circles are the averages of experimental points.

The addition of calcium(II) nitrate did not affect the spectra of H(MeTPP) and metalloporphyrins. Moreover, the rate was not also affected by introduction of $Ca(NO_3)_2$ up to 0.322 mol $\mathrm{kg^{-1}}$. The absence of any salt effect is consistent with the porphyrin reacting as free base.

The important role of water in the formation of metalloporphyrins has been demonstrated in some systems.[13] We checked the effect of water on the rate in the present systems. The introduction of water up to 0.1 mol $\mathrm{kg^{-1}}$ into the zinc(II) and cobalt(II) systems did not appreciably affect the rate constants. Since the water concentration of our systems is at most ca. 5×10^{-3} mol $\mathrm{dm^{-3}}$, we believe with confidence that the presence of water, if any, did not affect our results. DMF should strongly solvate metal ions and compete well against trace levels of water for the coordination site of metal ions.

The values of activation volumes are all positive. The positive activation volume strongly points to a dissociative character of the activation process, as suggested previously.[2,14] Recently Merbach et al.[15] have reported that the activation volumes for the DMF exchange at cobalt(II) and nickel(II) ions in DMF are 6.7 and 9.1 $\mathrm{cm^3\,mol^{-1}}$, respectively, at 296 K, and proposed a dissociative interchange (I_d) mechanism operative in the solvent exchange. The activation volumes for the metalation are approximately the same as for the exchange

---

(13) Lavallee, D. K.; Onady, G. M. *Inorg. Chem.* **1981**, *20*, 907.
(14) Hambright, P.; Chock, P. B. *J. Am. Chem. Soc.* **1974**, *96*, 3123.
(15) Meyer, F. K.; Newman, K. E.; Merbach, A. E. *Inorg. Chem.* **1979**, *18*, 2142.

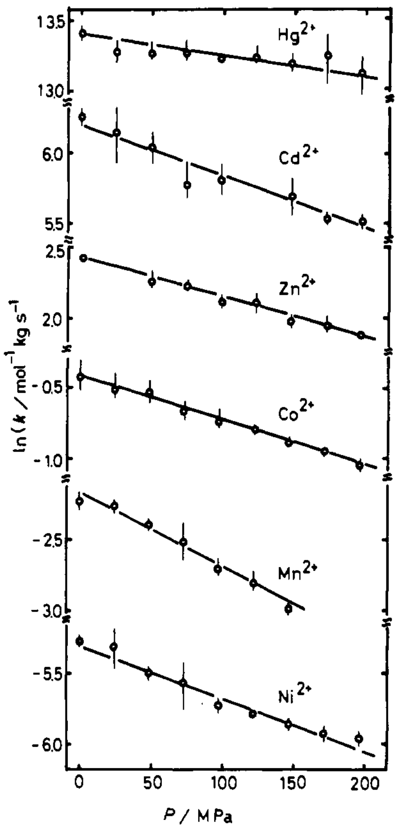


Figure 3. Pressure dependence of second-order rate constants. k is given in $\mathrm{mol^{-1}\ kg\ s^{-1}}$. Solid lines represent straight lines calculated by using the rate constants and activation volumes obtained. Each point represents the average of several determinations.

of DMF at the Co(II) and Ni(II) ions.

On the other hand, from the fact that values of $\Delta V_{ex}^{\neq}$ for solvent exchange on Mn^{2+} ion are $-5.4\ \mathrm{cm^3\ mol^{-1}}$ in water,[16] $-5.0\ \mathrm{cm^3\ mol^{-1}}$ in methanol,[17] and $-7.0\ \mathrm{cm^3\ mol^{-1}}$ in acetonitrile,[18] Merbach[19] has proposed an I_a mechanism operative in the solvent exchange at the manganese(II) ion. The most striking result is that in the present system, however, $\Delta V^{\neq}$ for the manganese(II) ion incorporation is $12.9 \pm 0.8\ \mathrm{cm^3\ mol^{-1}}$. Even in the Mn(II) reaction, it may be difficult for a cyclic ligand such as H(MeTPP) to make a metal–ligand bond before loosening of the metal–solvent bond. Thus, in the metalloporphyrin formation it is not easy to generate the transition state for an associative activation. Since this situation is the case for all systems, each $\Delta V^{\neq}$ is positive.

The rate of metalloporphyrin formation has been claimed to be parallel with the rate of solvent exchange at the relevant metal ion.[2,14] From the rate constant of porphyrin metalation, k, and the solvent exchange in DMF, k_{ex}, ($\log k_{ex} - \log k$) is calculated for a series of the studied divalent metal ions and the values are given in the last column of Table I. The ratio k_{ex}/k decreases from manganese to mercury. Too high a value for manganese should be attributable to the difference in mechanism: associative interchange for solvent exchange vs. dissociative interchange for metalloporphyrin formation. It has been previously stated that the less dissociative the reaction mechanism, the lower the activation enthalpy.[20] The anomalous value of k_{ex}/k observed in the manganese incorporation into 5,10,15,20-tetrakis(*N*-methyl-4-pyridyl)porphine has been interpreted by the reaction product being Mn(III) porphyrin.[14] However, it more likely results from the mechanistic difference between the solvent exchange and the metalloporphyrin formation. The reaction product in the present study is not a Mn(III) porphyrin but a Mn(II) porphyrin. The complexation with an associative mode of activation may change the mechanism from "associative" to "dissociative" because of the steric factors of both the solvent and the entering ligand.[21]

For cobalt, nickel, and zinc, the metalloporphyrin formation proceeds through an interchange mechanism with a dissociative character similar to that of the solvent exchange as judged from the values of activation volume. If one assumes, for these metal ions, the rapid deformation equilibrium of porphyrin nucleus preceding the rate-determining solvent loss,[22] one has

$$k = K_{os}K_{D}k_{ex} \qquad (2)$$

where K_{os} and K_D refer to the formation constant of the outer-sphere complex and deformation equilibrium constant, respectively. Since porphyrin reacts as a neutral form, $\log K_{os}$ is calculated as -0.50 according to the Fuoss–Eigen equation. Then we have similar values of $\log K_D = -5.51$ to -5.19 for these three metal ions. That is to say, for instance, $30\ \mathrm{kJ\ mol^{-1}}$ are needed to realize the deformation of porphyrin favorable for the Ni(II) porphyrin formation with H(MeTPP).

The ratio k_{ex}/k is lower for cadmium incorporation. This is just as observed for the cadmium incorporation into 5,10,15,20-tetrakis(4-phenylsulfonato)porphine in aqueous solution.[23] The ratio k_{ex}/k is lowest for mercury incorporation into H(MeTPP). If we assume the rate constant for the cadmium and mercury incorporation to be given also by eq 2, a slight deformation of porphyrin with a small needed energy will suffice for the metalloporphyrin formation of these large metal ions. These metal ions cannot fit into the porphyrin ring.[6] Thus, the extent of the porphyrin deformation needed for the metal ion incorporation should be different for different pairs of porphyrin and metal ions. Only $12\ \mathrm{kJ\ mol^{-1}}$ are required for the deformation of porphyrin prior to the formation of $Hg(MeTPP)^+$ in DMF.

Moreover, the rates for complexation of H(MeTPP) are slower than those for the corresponding solvent exchange, but faster than the rates for complexation of planar nonmethylated tetraphenylporphine.[2,24,25] These facts indicate the deformation of the porphyrin as a rapid process occurring before the rate-determining step.[2,14,25,26]

Acknowledgment. S.F. gratefully acknowledges financial support of this work by the Tokai Gakujutsu Shinkokai Foundation (1982).

Registry No. H(MeTPP), 51552-53-5; Mn, 7439-96-5; Co, 7440-48-4; Ni, 7440-02-0; Zn, 7440-66-6; Cd, 7440-43-9; Hg, 7439-96-5.

---

(16) Ducommun, Y.; Newman, K. E.; Merbach, A. E. *Inorg. Chem.* **1980**, *19*, 3696.

(17) Meyer, F. K.; Newman, K. E.; Merbach, A. E. *J. Am. Chem. Soc.* **1979**, *101*, 5588.

(18) Sisley, M. J.; Yano, Y.; Swaddle, T. W. *Inorg. Chem.* **1982**, *21*, 1141.

(19) Merbach, A. E. *Pure Appl. Chem.* **1982**, *54*, 1479.

(20) Tanaka, M. *Inorg. Chim. Acta* **1981**, *54*, L129.

(21) Ishihara, K.; Funahashi, S.; Tanaka, M. *Inorg. Chem.* **1983**, *22*, 3589.

(22) Turay, J.; Hambright, P. *Inorg. Chem.* **1980**, *19*, 562. These authors proposed that the observed rate constant would take the form $k_{obsd} = K_{os}K_Dk_{ex}k_H$. This form is quite unusual in that k_{obsd} involves the product of two rate constants. More recently Lavallee and Onady reported that N–H bond breaking is not rate determining.[13]

(23) Tabata, M.; Tanaka, M. *J. Chem. Soc., Dalton Trans.* **1983**, 1955.

(24) Rate constants for reactions of $H_2(TPP)$ with Cd(II) and Hg(II) in DMF at 25 °C are $(6.5 \pm 1.5) \times 10^{-3}\ \mathrm{mol^{-1}\ dm^3\ s^{-1}}$ (ref 1) and $(1.7 \pm 0.3) \times 10^{3}\ \mathrm{mol^{-1}\ dm^3\ s^{-1}}$ (Funahashi, S.; Yamaguchi, Y.; Tanaka, M., unpublished results), respectively.

(25) Shah, B.; Shears, B.; Hambright, P. *Inorg. Chem.* **1971**, *10*, 1828.

(26) Lavallee, D. K.; Anderson, O. P. *J. Am. Chem. Soc.* **1982**, *104*, 4707.