radicals are not involved[17] in the uninitiated reaction, contrasts sharply with the results of others on the radical-initiated reaction at higher temperatures.[18-21] Moreover, it indicates that acyl radicals are *not* involved in ester formation, as originally postulated.[5,6] This last conclusion receives further support for our observation that absolutely no $Me_3C(O)OCH_2CMe_3$ was produced when 0.2 M $Me_3CONNOCMe_3$ was completely decomposed in 7.4 M Me_3CCHO in benzene at 30 or 60 °C.[23] The detected decrease in the aldehyde concentration was 2 M at both temperatures, but the only aldehyde derived product was isobutane. We are currently investigating the mechanism of ester formation.

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Registry No. n-Bu_3SnD, 688-73-3; Me_3CCHO, 630-19-3; $Me_3CONNOCMe_3$, 14976-54-6; Me_3CCOCl, 3282-30-2; Cl_2, 7782-50-5; H_2, 1333-74-0; $Me_3C\dot{C}{=}O$, 50694-27-4.

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Rapid Incorporation of Copper(II) in Porphyrin Derivatives

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The mechanism by which metal ions are incorporated into porphyrins and substituted porphyrins has been intensively investigated without establishing a definitive mechanism[1-4] It has been suggested that the mechanism includes an association between the free or complexed metal ion and the porphyrin.[5-7] Normally, these reactions are quite slow, with the rate-determining step being variously attributed to deformations of the rigid porphyrin plane,[7,8] proton dissociation by an active metal complex,[5,6] or complex formation with the porphyrin[4] or porphyrin substituents.[7]

Table I. Observed Rate Constants for Incorporation of Cu(II) into Tetraphenylporphine (TPP) and Several *meso*-α,α,α,α-Tetrakis(*o*-acylamidophenyl)porphine ($\alpha^4H_2T_{acyl}PP$) Derivatives[a]

compd	K_{obsd}, h^{-1}	compd	K_{obsd}, h^{-1}
TPP	0.040	$\alpha^4H_2T_{lauroyl}PP$	1.019
$\alpha^4H_2T_{palmitoyl}PP$	0.999	$\alpha^4H_2T_{decanoyl}PP$	1.119
$\alpha^4H_2T_{myristoyl}PP$	1.074		

[a] $[Cu^{2+}] = 0.04$ M.

We have investigated the incorporation of Cu(II) into derivatives of *meso*-tetraphenylporphine (TPP) in nondetergent microemulsions over a nominal pH range of 1.00–4.00. The kinetic data for a number of coordinating and noncoordinating ligands clearly show that very fast rates of metal incorporation depend on the formation of a reactive metal complex as previously postulated.[3,4,6,8] The slow step apparently involves an outer-sphere association between the reactive intermediate and the porphyrin followed by rapid metal incorporation.

Under pseudo-first-order conditions the reaction is first order in Cu(II) concentration. Plots of $-\ln(A_\infty - A_t)$ vs. time were linear, and varying initial concentrations gave the same slope.

The reaction is zero order in $[H^+]$ over a pH range of 2.00–4.00 but inverse half order below pH 2.00. The rates of metal incorporation for the 10–16 carbon derivatives, *meso*-α,α,α,α,-tetrakis(*o*-acylamidophenyl)porphine, $\alpha^4H_2T_{acyl}PP$, are approximately 25 times faster than that for TPP itself (Table I). Observed rate constants for several ligands have been obtained. These rates correlate approximately with E_n, the ligand nucleophilicity parameter described by Edwards.[10]

Metalation reaction between $\alpha^4H_2T_{pal}PP$ (pal = palmitoyl) and various cupric salts have been examined in a detergent-free microemulsion. A composition of toluene, 2-propanol, and water (mole fractions 0.36, 0.44, and 0.20, respectively) exhibits characteristics similar to detergent-stabilized microemulsions.[11] The acylated TPP derivative is a surface-active porphyrin possessing four 16-carbon chains preferentially solubilized in the toluene-rich continuum and an aromatic porphyrin ring with four imine nitrogens solubilized in the 2-propanol-rich region.

meso-α,α,α,α-Tetrakis(*o*-aminophenyl)porphine[11] was acylated with palmitoyl chloride, which upon subsequent workup and crystallization produced the surface-active porphyrin in 90% yield.. These violet crystals show a single spot on TLC (1:1 benzene–ether) and exhibit maxima at 645, 587, 543, 519, and 450 nm (Soret). The aqueous phase was adjusted to pH 3.00 prior to forming the microemulsion. At pH 3.00 and a concentration of 8.50×10^{-5} M in toluene the porphyrin exists primarily as the free base.

All kinetic studies were run under pseudo-first-order conditions where Cu(II) concentrations ranged from 0.01 to 0.10 M, with the Cu(II) concentrations always in approximately 100-fold excess with respect to porphyrin. Spectra were followed over at least 7 half-lives on a Varian Cary 219 recording spectrophotometer for the slower reactions or a stopped-flow spectrophotometer interfaced to an Amino-Morrow storage and retrieval system for faster reactions. The kinetic runs were carried out by rapid mixing of two solutions: the first contained appropriate amounts of 2-propanol, water, Cu(II), and anion; the second contained toluene and porphyrin. Kinetic data were obtained by following the appearance of the Cu(II)–porphyrin band at 540 nm. The temperature was held to 25.0 ± 1.0 °C.

Previous studies have suggested that the controlling feature of porphyrin metalation is the nature of the porphyrin itself. More recently, evidence has been presented that the nature of the reactive

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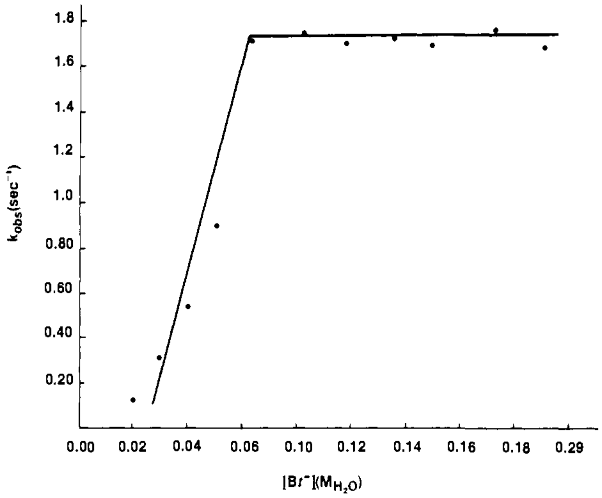

Figure 1. Observed rate constant as a function of bromide concentrations for $[Br^-] = 0.01–0.17$ M, $[Cu^{2+}] = 0.02$ M, and *p*H 3.00.

metal intermediate is, in fact, responsible for rapid metal incorporation.[3,4,6,7] Our results confirm these observations for we have found significant rate enhancement for metalation reactions by Cu(II) when coordinated to nucleophiles such as bromide ion. With a Cu(II) concentration of 0.02 M in water, addition of sodium bromide increases the rate of reaction from 8.05×10^{-5} to 1.45 s^{-1} relative to the rate when Cu(II) is present as copper(II) perchlorate. The reactive metal species is evidently the monobromide complex, $CuBr^+$ ($CuBr^+$, A_{max} 280 nm in H_2O, A_{max} 308 nm in 1:10 H_2O–2-propanol).[13] There is a first-order dependence on bromide ion over a concentration range 0.01–0.04 M in water (Figure 1; $[Br^-]:[Cu^{2+}] = 0.5–2$). Over a bromide concentration range 0.05–0.17 M ($[Br^-]:[Cu^{2+}] = 2.5–8.5$) no dependence on bromide ion was found. All data were fitted with a least-squares program: correlation values were greater than 0.98.

The reaction is pH independent in the region from pH 2.00 to 4.00. Previous investigations have found very slow reactions when the porphyrin is fully protonated. We also observe very slow reaction rates in the pH >2.00 region when the reactive metal species is the aquated copper(II) ion. However, when the concentration of bromide ion is >0.04, that is, when $CuBr^+(aq)$ is the reactive species, we observe a 10^4 *increase* in observed rate (Table II).

The above observations are consistent with the mechanism of eq 1–3.

$$Cu^{2+} + Br^- \rightleftharpoons CuBr^+ \qquad (1)$$

$$\alpha^4H_2T_{pal}PP + CuBr^+ \overset{K}{\rightleftharpoons} \alpha^4H_2T_{pal}PP + CuBr^+ \qquad (2)$$

$$\alpha^4H_2T_{pal}PP + CuBr^+ \xrightarrow{k} \alpha^4T_{pal}PPCu + Br^- + 2H^+ \qquad (3)$$

Under the conditions noted above step 1 is fully equilibrated prior to measurement of reactions rates. The mechanism gives the following rate law assuming that eq 2 is steady-state controlled:

$$k_{obsd} = kK[CuBr^+]/(1 + K[CuBr^+]) \qquad (4)$$

In eq 4 K is the equilibrium constant for eq 2, $[CuBr^+] > [\alpha^4H_2T_{pal}PP]$, and it is assumed that $k \ll K_{reverse}$. At low bromide concentrations ($[Br^-]:[Cu^{2+}] = 0.5–2$) the rate of metalation increases in accord with eq 4. Above a $[Br^-]:[Cu^{2+}]$ ratio of ~2.5 all $[Cu^{2+}]$ is present as $CuBr^+$; therefore, no further rate enhancement is experienced upon addition of further bromide.

In the low pH region (below pH 2.00) the porphyrin exists primarily as the unreactive (green) dication. We observe reduced rates in agreement with previous observations.[5,7,13] However, at higher concentrations of bromide the observed rates are still quite fast even at pH 1.00. (Table II, Figure 2).

Table II. Observed Rate Constants (h^{-1}) for Incorporation of Cu(II) into $\alpha^4H_2T_{pal}PP$ as a Function of pH[a]

metalating species	pH 1.00	pH 3.00
Cu^{2+}	0.0453	0.2898
$CuBr^+$	494.25	5562.00

[a] $[Cu^{2+}] = 0.02$ M; $[CuBr^+] \simeq 0.02$ M. The hydrogen ion concentration was adjusted with perchloric acid.

Table III. Observed Rate Constants and Half-Lives for Several Coordinating Nucleophiles[a]

N	k_{obsd}, s^{-1}	$t_{1/2}$, s	E_n^a
O_2^-	2.468	0.281	1.73
Br^-	1.454	0.477	1.51
Cl^-	0.675	1.027	1.24
$C_6H_5NH_2$	0.022	31.500	1.78
CH_3COO^-	2.880×10^{-3}	2.410×10^2	0.95
NO_3^-	3.340×10^{-3}	2.075×10^2	0.29
H_2O	8.050×10^{-5}	8.609×10^3	

[a] E_n^a is a nucleophilicity constant defined in ref 10; [ligands] = 0.08 M, $[Cu^{2+}] = 0.04$ M.

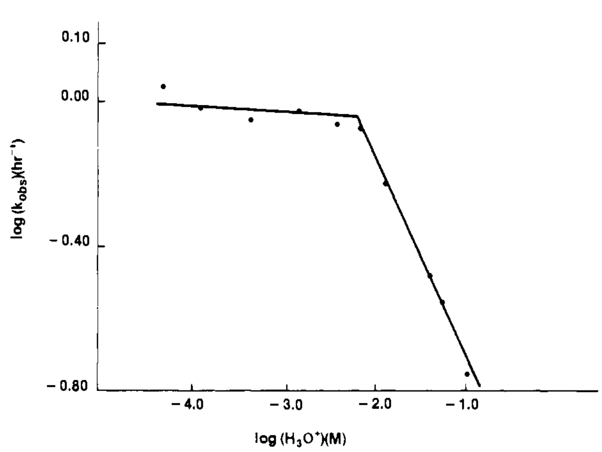

Figure 2. Observed rate constant as a function of Cu(II) into $\alpha^4H_2T_{pal}PP$ as a function of pH; $[Cu^{2+}] = 0.02$ M.

Similar results are obtained for a series of coordinating nucleophiles as indicated in Table III. Rate enhancement relative to the hexaaquacopper(II) species follows the order $NO_2^- > Br^- > Cl^- > C_6H_5NH_2 > CH_3CO_2^- > H_2O$. The trend for rate enhancement parallels the relative nucleophilicity[9] for these anions. The exception is aniline, perhaps due to a negative steric contribution.

Our results clearly show that the rate of metal incorporation into porphyrins is nearly independent of the nature of the porphyrin itself. Although half-lives of 0.2 s^{-1} have been observed for incorporation of Cu(II) via coordination of the copper ion to a carboxylate "picket fence",[9] we find that a direct binding site on the porphyrin is not necessary for rapid metalation. Rather, significant rate enhancement depends upon labilizing coordinated, inner-sphere water ligands. The stronger the nucleophile the weaker the bonds between the remaining aqua ligands become. As the lability of the Cu(II) sphere of hydration is increased, bonding between Cu(II) and imine nitrogen of the porphyrin is enhanced. That is, bond formation between Cu(II) and the ring nitrogens is directly related to the reactivity of the metalating species.

Registry No. Cu, 7440-50-8; TPP, 917-23-7; $\alpha^4H_2T_{pal}PP$, 68561-00-2; $\alpha^4H_2T_{myristoyl}PP$, 85849-95-2; $\alpha^4H_2T_{lauroyl}PP$, 85111-00-8; $\alpha^4H_2T_{decanoyl}PP$, 85828-69-9; O_2^-, 14915-07-2; Br^-, 24959-67-9; Cl^-, 16887-00-6; $C_6H_5NH_2$, 62-53-3; CH_3COO^-, 71-50-1; NO_3^-, 14797-55-8; H_2O, 7732-18-5.

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