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Entropy, Enthalpy, and Side Arm Porphyrins. 1. Thermodynamics of Axial Ligand Competition between 3-Picoline and a Series of 3-Pyridyl Ligands Covalently Attached to Zinc Tetraphenylporphyrin

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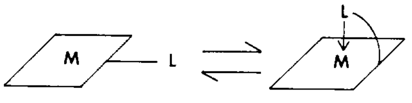
Abstract: A series of five-coordinate zinc tetraphenylporphyrins, each with a covalently attached 3-pyridyl side chain of different length, were synthesized. NMR spectroscopy was used to study the displacement of the 3-pyridyl ligand by free 3-picoline in toluene-d_8 solution. Values of K_{eq}, ΔH, and ΔS were dependent on the number of atoms in the chain. In all cases, 3-picoline formed a stronger bond with these zinc porphyrins than did the covalently attached pyridyl ligands. The entropy of free internal rotation of the atoms of the uncoordinated pyridyl side chain was an important factor in the entropy of displacement of the covalently attached pyridyl group. Measurement of the thermodynamic quantities for 3-picoline addition to a series of structurally related four-coordinate zinc porphyrins revealed the importance of bulky groups in preventing tight solvation of the porphyrin ring in the region of the binding site, thus increasing the stability and bond strength of the 3-picoline complex.

Introduction

The syntheses of a number of five- and six-coordinate metalloporphyrins and -chlorins in which the axial ligand(s) is covalently attached to the porphyrin ring have been reported over the past few years[3-14] because their investigation has become an important means of obtaining information concerning the metal center of various heme proteins. Covalent attachment of the axial ligand(s) assures the desired coordination number and the identity of ligand atoms bound to the metal and provides access to pure compounds of otherwise unstable coordination geometry such as five-coordinate Fe(II). Covalent attachment of axial ligands thus mimics the active site of various heme proteins in which axial ligands are provided to the heme by side chains of the protein which extend into the active site pocket in the geometry which nature has dictated.

Considerable discussion of the virtues of covalent attachment of axial ligands in terms of their providing a "high local concentration" of ligand and producing the desired coordination geometry has been presented.[10-12] Several studies of the effects (or lack thereof) of covalent attachment of a fifth ligand on the thermodynamics or kinetics of addition of a sixth ligand such as CO or O_2 to metalloporphyrins have been reported,[11,12] but no study has been presented on the actual thermodynamic stability of binding of the covalently attached axial ligand (1) relative to an analogous free ligand (2). Since the equilibrium constants have different units for reactions 1 and 2, they cannot be compared directly, but rather K_1 may be compared to K_2 multiplied by some reference concentration of base, for example, 1 M. That is, the value of K_1 is best compared to the ratio of the concentrations of product over reactant in the presence of a ligand concentration of 1 M for reaction 2. In terms of the enthalpy and entropy contributions to ΔG and thus K_{eq}, the difference in units for reactions 1 and 2 has no effect on ΔH, which is simply a measure of the metal–ligand bond strength in either case. The ΔS of each reaction is a measure of the increase in order in the system as a result of the reaction, and can be decomposed into the expected contributions to order in each case. In the gas phase, one would expect ΔS for reaction 2 to be much more negative than for reaction 1 because of the loss of translational and rotational entropy of L. Assuming no M–L bond strain in the product of reaction 1 and equal basicities for the ligand donor atoms of reactions 1 and 2, ΔH for the two reactions should be the same, leading to a less negative ΔG and smaller K_{eq} for reaction 2 than for reaction 1. In noncoordinating solvents, one would expect the same to be true but perhaps to a lesser extent depending upon the importance of solvation.



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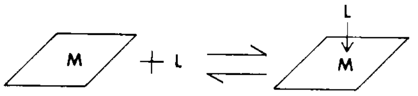

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In the course of preparation and study of six-coordinate metalloporphyrins as models of the cytochromes b[15] the question of the effect of covalent attachment on the stability of metal–ligand complexes became important, and a systematic study of the thermodynamics of covalently attached axial ligand binding in five-coordinate zinc(II) and six-coordinate cobalt(III) porphyrins was undertaken. Herein are reported the results of the study

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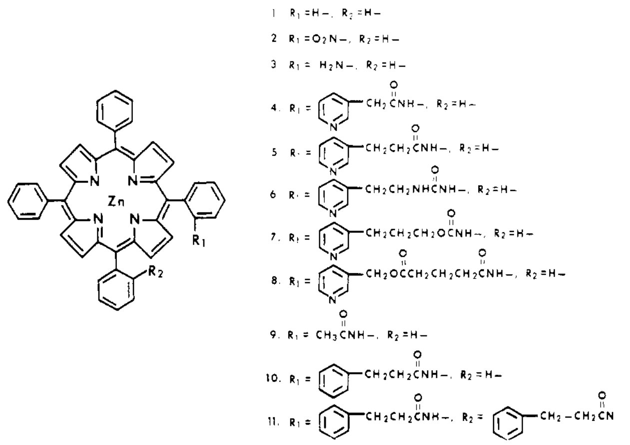
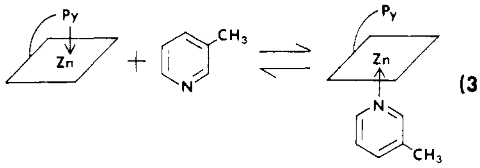


Figure 1. Structures of the zinc porphyrins of this study.

involving five-coordinate zinc(II).

The crystal and molecular structure of several five-coordinate zinc porphyrins[16-18] and one five-coordinate zinc porphyrin cation radical[19] show the zinc atom to be out of the plane of the porphyrin nitrogens by 0.2–0.3 Å in the direction of the fifth ligand. A similar out-of-plane distance is found in solution by NMR techniques.[20] This out-of-plane geometry has been used to explain why only one axial ligand can be added to zinc(II) porphyrins.[21-27] Because the thermodynamics of addition of a variety of axial ligands to ZnTPP[21-27] and its phenyl-substituted analogues[25] have been reported, and the electronic factors affecting complex stability have been well delineated, this system appeared to be an excellent choice for comparing the thermodynamics of reactions 1 and 2.

We have prepared the series of zinc(II) porphyrins shown in Figure 1 and investigated their visible and NMR spectra. It was found that the covalently attached pyridyl ligand of the zinc side arm porphyrins **4–8** was so fully bound to zinc that no detectable concentration of four-coordinate zinc porphyrin was present up to the boiling point of toluene. Thus, reaction 1 could not be studied directly for **4–8**. However, addition of 3-picoline to the solution caused the pyridyl proton NMR peaks to shift downfield in a manner which indicated that 3-picoline competed with the covalently attached pyridyl ligand for the fifth coordination site (eq 3). Using the downfield shift of the protons of the side arm pyridyl, we have, therefore, investigated the thermodynamics of reaction 3 for **5**, **7**, and **8**, and using visible spectroscopy investigated reaction 2 for **1**, **9**, **10**, and **11**, and from these data derived the thermodynamics of reaction 1.



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Experimental Section

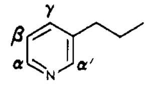
All of the porphyrin compounds were dried for several hours at 100 °C before use to remove traces of water and other neutrally charged Lewis bases. Failure to do so caused the NMR resonances of the pyridyl protons of the side arm of **4–8** to appear at lower fields than the values reported in Table I.

Table I. Chemical Shifts of Coordinated Pyridyl Protons in Toluene-d_8 at 25 °C

compd	α′	α	β	δ
4	2.323[a]	2.504[a]	5.499[a]	6.269[a]
5	2.195	2.476	4.524	5.006
6	2.14[b]	2.03[b]	4.583	5.042
7	2.509	2.322	4.577	5.161
8	2.728	2.520	4.544	5.344

[a] In $CDCl_3$.[41] [b] Resonances hidden under the toluene methyl peak. Estimated by extrapolation of the shifts as a function of added 3-picoline to the no-base positions.

Table II. Coupling Constants (Hz) Used in Computer Simulation of Spectra



$J_{\alpha'\alpha} = 0$

$J_{\alpha'\beta} = 0.5$ $J_{\alpha\beta} = 5.1$

$J_{\alpha'\gamma} = 2.2$ $J_{\alpha\gamma} = 1.7$ $J_{\beta\gamma} = 8.0$

The 3-picoline and pyridine used (Aldrich) were distilled and stored over molecular sieves (Linde 4A). The protonated toluene (Baker spectrophotometric grade) was shaken with and stored over molecular sieves. Deuterated benzene, chloroform, and toluene (Merck, Aldrich, and Stohler) were used as received.

The visible spectra were run on a Cary 17 recording spectrophotometer. At room temperature 10-mm cells were used. Above room temperature, thermostated bath water was circulated through a 5-mm jacketed cell (the reference cell was unjacketed). Cells were allowed to equilibrate for 20 min before the spectrum was recorded. The temperature inside the cell was measured by placing a copper–constantan thermocouple directly in the cell and reading the voltage (either with a digital voltmeter or with a potentiometer) relative to an ice–water mixture.

Stock solutions were prepared by volumetric dilutions of weighed amounts of **1**, **9**, **10**, and **11** and of the base. Successive 1:10 dilutions of the base were made to get suitable concentrations. A fixed aliquot of porphyrin and the desired amount of base were mixed and diluted to volume and the spectrum was recorded after thermal equilibration.

The NMR spectra used to check the identity of the compounds were obtained on a modified Varian HR-100 operating at 100 MHz or a Varian EM-390 operating at 90 MHz, both continuous-wave instruments. Data for most of the equilibrium studies were obtained on a JEOL PFT-100 Fourier transform instrument operating at 99.54 MHz. Accumulations (100 or 200) were block averaged in groups of 20, allowing the large solvent and 3-picoline peaks to overflow. Peak positions were determined with a peak-finding routine and measured relative to Me_4Si as internal standard. Resolution was 0.24 Hz (with the spectrum occupying 8K). The temperature was regulated with the JEOL variable-temperature apparatus and measured from the single pulse unlocked spectrum of either ethylene glycol or methanol NMR thermometers. Peak separations were converted to temperatures by the formulas of Van Geet and Kaplan et al.[28] It was found that after 10 min four successive readings could be obtained which were the same to within 0.13 K. Temperature measurements made at the beginning and end of each 5–6-h study showed a maximum temperature drift of 0.3 K.

A portion of porphyrin was weighed into an NMR tube in an appropriate amount of solvent. Me_4Si was added by bubbling through about 50 μL of vapor. This amount did not change the volume but was more than sufficient to give a strong reference peak. Successive additions of base were made by adding with a microliter syringe either a one-to-ten volumetric dilution or a pure aliquot of 3-picoline. Before accumulating the spectrum, the sample was allowed to thermally equilibrate for 10–20 min in the probe.

As the two α peaks of the pyridyl side arm moved downfield faster than the β and γ ones, overlap of peaks occurred at some of the base additions. The simulation program on the Nicolet 1080 computer was used to simulate these overlapped peaks. Estimates of the coupling constants were available from the initial porphyrin spectra where the resolution was good enough to measure the ortho and meta couplings.

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The one para coupling was set to 0.5 Hz (Table II). In most cases, changes in the input shifts of only 0.1 Hz were detectable in the simulated spectra.

Data Analysis. The Rose–Drago equation[29] to determine from UV or visible spectroscopic data the equilibrium constant for the formation of a 1:1 complex $A + B \rightleftharpoons C$ (K) was modified to calculate K from NMR chemical shift data, where, owing to fast exchange, only one NMR peak is seen at a shift δ_0 corresponding to the weighted average of the shifts of the cooridnated, δ_A, and uncoordinated, δ_c, covalently attached pyridyl protons:

$$\frac{1}{K} = B_0\left[\frac{\delta_c - \delta_A}{\delta_0 - \delta_A}\right] - A_0 - B_0 + A_0\left[\frac{\delta_0 - \delta_A}{\delta_c - \delta_A}\right] \qquad (4)$$

where A_0 and B_0 are the initial concentrations of acid and base. Because the uncoordinated pyridyl peaks of the 3-picoline-complexed forms of **4**–**8** are obscured by the pyrrole and aromatic peaks of the porphyrin, this is an equation in two unknowns (K and δ_c) which Rose and Drago[29] solve graphically. Because a graphical solution does not give an estimate of errors for K and δ_c, a computer program using Wentworth and Rosseinsky's[30–32] iterative, least-squares solution for nonlinear functions was written to solve (4) for the unknowns and their errors. The program was then modified for the visible spectral data that were acquired. Values of ΔH and ΔS were calculated from a weighted, least-squares fit[33] of ln K vs. $1/T$ data to a straight line.

Synthesis of Compounds. 5,10,15,20-Tetraphenylporphinoatozinc(II) (ZnTPP, 1) was synthesized and purified according to published procedures.[34,35]

5-(2′-Nitrophenyl)-10,15,20-triphenylporphyrin, H_2-mono-NO_2TPP, metal-free **2**, was prepared by the general method of Adler et al.:[34] 40.7 mL (0.4 mol) of benzaldehyde (Aldrich), 60.45 g (0.4 mol) of *o*-nitrobenzaldehyde (Aldrich), and 55.5 mL (0.8 mol) of pyrrole (Aldrich) were refluxed in 3 L of propionic acid (MCB) for 0.5 h. The solution was allowed to stand for 1 day, then filtered, washed with methanol, and dried; yield ca. 30 g of mixture of isomers. Approximately 100 mL of a saturated benzene solution of the above mixture of isomers was placed on a 3 cm × 1.3 m column packed with slurry of silica gel (Baker chromatographic grade) in benzene and eluted with benzene. The second band contained the desired metal-free **2**.

5-(2′-Aminophenyl)-10,15,20-triphenylporphyrin, H_2-mono-NH_2TPP, metal-free **3**, was prepared by reduction ($SnCl_2$/HCl) of metal-free **2** according to the general procedure of Collman et al.[36] and purified by column chromatography on silica gel, using methylene chloride as eluent.

5-{2′-[(3″-Pyridyl)methylcarbonylamino]phenyl}-10,15,20-triphenylporphinatozinc(II) (4). To a slurry of 868 mg (5 mmol) of 3-pyridylacetic acid hydrochloride (Aldrich) in 20 mL of dry methylene chloride were added 0.834 mL (10 mmol) of dry pyridine and 0.123 mL (1 mmol) of trimethylacetyl chloride. After the mixture was stirred for 1 h, 65 mg (0.1 mmol) of metal-free **3** dissolved in 15 mL of dry methylene chloride was added dropwise. After being stirred for 1 h more, the reaction mixture was washed several times with water, dried over Na_2SO_4, and evaporated to dryness. TLC on silica gel (Bakerflex) showed no evidence of starting material metal-free **3**. Zinc was inserted and the zinc porphyrin chromatographed as described for **5**; overall yield 35 mg (42%).

3-(3′-Pyridyl)propionic acid was prepared by chromic acid oxidation[31] of 3-(3-pyridyl)propanol (Aldrich). A solution of 100 g (0.73 mol) of 3-(3-pyridyl)propanol, 21 mL of concentrated H_2SO_4, and 75 mL of H_2O was added dropwise over a period of 3 h to a solution of 182 g (0.61 mol) of $Na_2Cr_2O_7{\cdot}2H_2O$, 119 mL of concentrated H_2SO_4, and 320 mL of H_2O. After the mixture was stirred for 1 h, a solution of 6.05 g (0.19 mol) of methanol in 18 mL of H_2O was added dropwise to consume the remaining dichromate. A slurry of 795 g (2.52 mol) of $Ba(OH)_2{\cdot}8H_2O$ in 1 L of H_2O was slowly added to the resulting solution. After being stirred for 2 h, the resulting mixture was centrifuged and the liquid decanted. The volume was reduced, the pH adjusted to 5.0, and the product crystallized by further reduction of the volume. The product was recrystallized from ethanol; yield 89 g (81%).

5-{2′-[2″-(3‴-Pyridyl)ethylcarbonylamino]phenyl}-10,15,20-triphenylporphinatozinc(II) (5). 3-(3-Pyridyl)propionic acid (60 mg, 0.4 mmol) was dissolved in 5 mL of *N,N*-dimethylformamide (DMF). A few molecular sieves (Linde 4A) were added, and the solution was allowed to sit overnight to remove traces of water from the acid. The dried solution was decanted and cooled in an ice bath, and 0.25 mL (0.35 mmol) of redistilled thionyl chloride added. After the solution was stirred for 1 h at room temperature, 44 mg (0.07 mmol) of metal-free **3** in 15 mL of dry DMF and an excess (about 5 drops) of dry pyridine were added. At the end of 1 h, the solution was diluted with water and the porphyrins were extracted with benzene; the benzene layer was washed several times with water, dried over Na_2SO_4, and evaporated to dryness. TLC on silica gel showed only traces of unreacted metal-free **3**. The product was chromatographed on silica gel, using 19:1 benzene–acetone; traces of unreacted metal-free **3** moved ahead of the product metal-free **5**; yield 45 mg (85%). To insert zinc, the metal-free **5** was refluxed for about 20 min in 20 mL of DMF with a tenfold excess of $Zn(OAC)_2$ plus 2 drops of pyridine. After cooling, the solution was diluted with water and extracted into benzene. The washed and dried benzene extracts were evaporated to dryness and chromatographed on a column of silica gel in benzene. The desired product **5** was eluted with 19:1 benzene–acetone; yield 30 mg (62%). Anal. Calcd for $C_{52}H_{36}N_6OZn$: C, 75.6; H, 4.39; N, 10.17; Zn, 7.90. Found: C, 75.9; H, 4.70; N, 9.65; Zn, 7.55. Mass spectrum: m/z 826, M − 92, M − 106, M − 134, M − 149, M − 183, M − 211, M − 226, M/2, and doubly charged ions of all of the above high molecular weight fragments.

2-(3′-Pyridyl)ethylamine was prepared by H_2/Raney nickel reduction of 25 g of 3-pyridylacetonitrile (Aldrich) according to the general procedure of Schwann[38] and purified by vacuum distillation (bp 100–120 °C, 1,5 mm); yield 5 g of a 2:1 mixture of starting material and product, or approximately 1.7 g of 2-(3-pyridyl)ethylamine (15%). NMR ($CDCl_3$): δ 2.74 (m, 4), 7.28 (m, 1), 7.70 (m, 1), 8.50 (s, 1), 8.62 (s, 1).

5-{2′-[2″-(3‴-Pyridyl)ethylaminocarbonylamino]phenyl}-10,15,20-triphenylporphinatozinc(II) (6). A solution of 42 mg (0.07 mmol) of metal-free **3** in 25 mL of dry benzene and 1 mL of dry pyridine was added dropwise to a solution of 1 mL (1.0 mmol) of 1 M phosgene in benzene plus 10 mL of dry benzene. After addition was complete, the solution was stirred for 0.5 h and then added dropwise to a solution of 1.6 g of the 2:1 mixture of 3-pyridylacetonitrile and 2-(3-pyridyl)ethylamine dissolved in 5 mL of dry methylene chloride. After addition was complete, the solution was stirred for 1 h, extracted with dilute HCl (pH ~2) until all nonporphyrinic pyridine derivatives had been removed, dried over Na_2SO_4, and evaporated to dryness. The product, metal-free **6**, was chromatographed, zinc inserted, and the zinc porphyrin **6** chromatographed as described for **5**; yield 32 mg (57%).

5-{2′-[3″-(3‴-Pyridyl)propoxycarbonylamino]phenyl}-10,15,20-triphenylporphinatozinc(II) (7). This compound was prepared and purified in a manner similar to **6**, substituting 2 mL of 3-(3-pyridyl)propanol (Aldrich) for the 2-(3-pyridyl)ethylamine; yield 69%.

5-[2′-(3″-Pyridylmethyleneoxy-1‴-carbonyl-3‴-propylcarbonylamino)phenyl]-10,15,20-triphenylporphinatozinc(II) (8). A mixture of 1.14 g (10 mmol) of glutaric anhydride and 1.09 g (10 mmol) of 3-pyridylcarbinol was heated without solvent. Redistilled thionyl chloride (1 mL) was added to 88 mg (0.4 mmol) of the resulting solid 3-pyridylmethoxycarbonylbutanoic acid. Ten minutes later, 2 mL of dry benzene was added and the solution evaporated to dryness under vacuum. Again, 2 mL of benzene was added, and the solution evaporated to remove excess thionyl chloride. The product was reacted with 50 mg (0.08 mmol) of metal-free **3** as described for **5**. Zinc insertion and purification were carried out as described for **5**; yield 27 mg (38%).

5-[2′-(Methylcarbonylamino)phenyl]-10,15,20-triphenylporphinatozinc(II) (9). Metal-free **3** (94 mg, 0.15 mmol) was dissolved in 25 mL of dry benzene. A solution of 0.12 mL (1.75 mmol) of acetal chloride in 2 mL of benzene was then added, followed by 10 drops of dry pyridine. After being stirred for 1 h, the benzene solution was washed with water, dried over Na_2SO_4, and evaporated to dryness. Zinc insertion and purification were carried out as described for **5**; yield 92 mg (84%).

5-[2′-(2″-Phenylethylcarbonylamino)phenyl]-10,15,20-triphenylporphinatozinc(II) (10). It was found that a simpler procedure than that described for synthesis of compound **5** could be used in general for acid chloride formation and coupling of aryl-, alkyl-, and some pyridylalkylcarboxylic acids. To 70 mg (0.4 mmol) of hydrocinnamic acid (Aldrich) was added 1 mL of redistilled thionyl chloride. After the solution had stood for 10 min, 2 mL of dry benzene was added, and the solution evaporated to dryness under vacuum. Another 2 mL of dry benzene was added and the solution again evaporated to dryness. The acid chloride thus formed was dissolved in 5 mL of dry methylene

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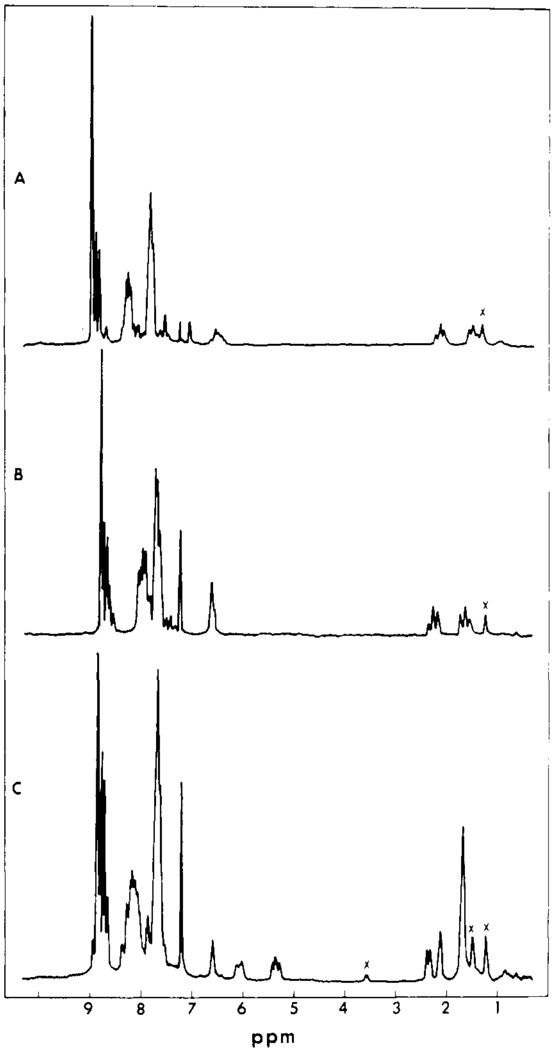

Figure 2. ^{1}H NMR spectra of derivatives of **5** in $CDCl_3$: (a) $H_2TPPNHCO(CH_2)_2C_5H_4N$; (b) $NiTPPNHCO(CH_2)_2C_5H_4N$; (c) $ZnTPPNHCO(CH_2)_2C_5H_4N$.

chloride to which 3 drops of dry pyridine had been added, and the resulting solution was added dropwise to a solution of 51 mg (0.08 mmol) of metal-free **3** in 15 mL of dry methylene chloride. The reaction mixture was stirred for 0.5 h, washed several times with water, dried over Na_2SO_4, and evaporated to dryness. TLC showed no evidence of the starting material, metal-free **3**. Zinc was inserted as described for **5**; yield 45 mg (69%). Anal. Calcd for $C_{53}H_{37}N_5OZn$: C, 77.1; H, 4.52; N, 8.49; Zn, 7.95. Found: C, 77.4; H, 4.86; N, 8.25; Zn, 7.35.

5α,10β-Di[2′-(2″-phenylethylcarbonylamino)phenyl]-15,20-diphenylporphinatozinc(II) (11). The preparation of the diamino-TPP starting material for this compound will be described elsewhere.[15] The false side arms were added as described for **9**, except that the quantities of hydrocinnamic acid and pyridine were doubled. Zinc was inserted as described for **5**; yield 46%.

Results

To demonstrate that a covalently attached pyridine does coordinate with the central zinc atom, spectra (visible and NMR) of compounds having pyridyl side arms, **4**–**8**, were compared with those lacking such an arm (**1**, **9**–**11**). Figure 2 shows a comparison of the ^{1}H NMR spectra of **5** and its metal-free and nickel(II) derivatives. Neither the metal-free nor Ni(II) derivatives show any peaks in the region from 2.4 to 6.4 ppm, whereas the Zn(II) complex **5** has peaks at 2.17, 2.40, 5.38, and 6.10 ppm in $CDCl_3$ having couplings (Table II) and integrated areas consistent with their assignment as the four protons on a 3-substituted pyridine ring. For the two α protons, this amounts to an upfield shift of about 6 ppm, which is attributed to the effect of the porphyrin ring current.[20,38] On the other hand, the ^{13}C NMR spectra of these compounds[40] do not show this dramatic upfield shift of the coordinated side arm pyridyl carbons. Table I lists the chemical shifts of the pyridyl protons of the zinc side arm porphyrins **5**–**8** in toluene-d_8 and **4** in $CDCl_3$[41] at room temperature. All pyridyl protons shift downfield as the temperature increases while the pyrrole protons shift slightly upfield with increasing temperature, but none of the shifts are affected by zinc porphyrin concentration over the range 1×10^{-2} to 1×10^{-3} M, and a Beer's law plot over the concentration range 6.8×10^{-3} to 6.8×10^{-8} M shows no evidence of aggregation.

Table III. Visible Spectra of Zinc Porphyrins in Toluene without and with Excess 3-Picoline

	λ_{max}, nm	
compd	without 3-picoline	with 3-picoline
1	549, 588	562, 601
9	549, 588	561, 601
10	550, 588	562, 601
11	549, 587	562, 601
4	559, 597.5	562, 601
5	563, 602	562, 601
6	562, 601	562, 601
7	561, 601	561, 601
8	562, 601	562, 601

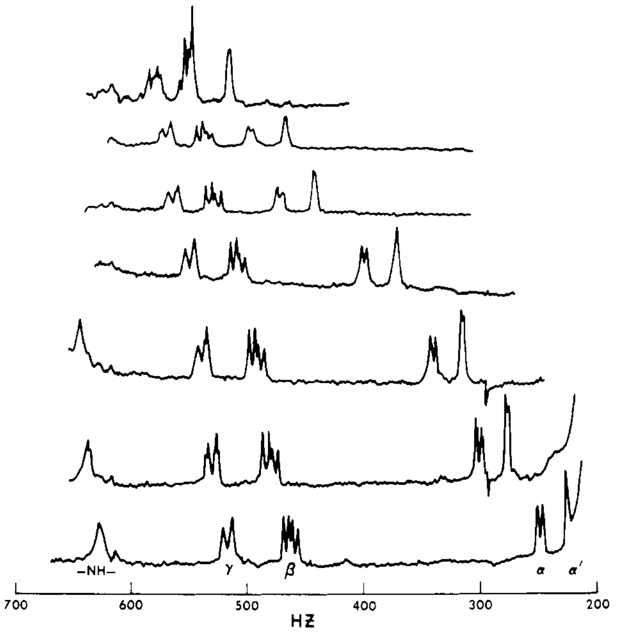

Figure 3. The 99.5-MHz ^{1}H NMR spectra of the pyridyl proton peaks of **5** in toluene-d_8 solution (bottom) as aliquots of 3-picoline are added.

Table III shows the positions of the wavelength maxima of the α and β electronic absorption bands for the compounds of this study in toluene both without and with added 3-picoline. No change in the absorption maxima or absorbance was observed on addition of 3-picoline to **5**–**8**, but the spectrum of **4** shifted slightly on addition of 3-picoline. However, the shape of the absorption band and the bandwidths of **4** were not affected by either 3-picoline addition or raising the temperature to 80 °C, indicating either that the covalently attached pyridyl is completely bound up to 80 °C or that K_1(353 K) $\geq$ 20, and that the shifted wavelength maxima of **4** arise from perturbations of the π orbitals of the porphyrin ring caused by the binding of this very short covalently attached pyridyl.

Figures 3 and 4 give two examples of the downfield shift of the pyridyl protons as increasing amounts of 3-picoline are added. The progress of this downfield shift was recorded in duplicate for compounds **5**, **7**, and **8** at −24, 24, 50, and 78 °C. From the

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(39) C. B. Storm and A. H. Corwin, *J. Org. Chem.*, **29**, 3700 (1964).

(40) F. A. Walker and M. Benson, manuscript in preparation.

(41) Compound **4** is extremely insoluble in toluene and satisfactory spectra could not be obtained.

Table IV. Equilibrium Constants as a Function of Temperature, ΔH, and ΔS for the Reaction of 3-Picoline with Compounds **5**, **7**, and **8**

Compound **5**, $K_3{}^a$ calcd from proton

T, K	α'	α	β	γ
351.0	4.68 ± 0.25	4.77 ± 0.25	5.34 ± 0.38	5.82 ± 0.47
351.0	3.98 ± 0.24	4.04 ± 0.24	4.01 ± 0.36	3.98 ± 0.42
323.1	5.70 ± 0.28	5.77 ± 0.28	5.48 ± 0.39	5.49 ± 0.45[
323.3	5.35 ± 0.41	5.44 ± 0.41	5.57 ± 0.57	4.55 ± 0.62
296.8	8.32 ± 0.35	8.13 ± 0.35	7.28 ± 0.57	6.15 ± 0.62
296.8	8.50 ± 0.37	8.21 ± 0.51	7.86 ± 0.53	6.45 ± 0.55
248.7	23.9 ± 2.5	24.1 ± 2.5	15.6 ± 3.0	*b*
248.2	23.2 ± 4.7	23.1 ± 5.0	24.6 ± 11.4	*b*
ΔH_3, cal/mol	−2790 ± 140	−2670 ± 150	*c*	*c*
ΔS_3, cal/(deg·mol)	−5.1 ± 0.5	−4.7 ± 0.5		

Compound **7**, $K_3{}^a$ calcd from proton

T, K	α'	α	β	γ	NH
350.2	1.50 ± 0.10	1.54 ± 0.09	1.47 ± 0.13	1.43 ± 0.17	1.02 ± 0.11
350.3	1.46 ± 0.09	1.46 ± 0.09	1.38 ± 0.14	1.31 ± 0.17	0.90 ± 0.11
323.3	2.06 ± 0.13	2.07 ± 0.12	1.97 ± 0.18	1.78 ± 0.23	1.27 ± 0.15
323.3	1.62 ± 0.10	1.62 ± 0.10	1.51 ± 0.14	1.73 ± 0.20	0.90 ± 0.11
295.8	1.93 ± 0.21	1.92 ± 0.20	1.88 ± 0.29	1.70 ± 0.36	*b*
298.3	2.04 ± 0.21	2.04 ± 0.20	1.96 ± 0.35	2.15 ± 0.51	*b*
247.8	2.74 ± 0.51	2.97 ± 0.51	2.47 ± 0.66	2.13 ± 0.80	1.26 ± 0.78
248.0	2.32 ± 0.58	2.50 ± 0.57	2.18 ± 0.73	1.71 ± 0.90	0.86 ± 0.79
ΔH_3, cal/mol	−1035 ± 220	−1077 ± 207	*c*	*c*	*c*
ΔS_3, cal/(deg·mol)	−2.1 ± 0.7	−2.2 ± 0.6			

Compound **8**, $K_3{}^a$ calcd from proton

T, K	α'	α	β	γ
278.6	26.0 ± 2.3	25.0 ± 2.3	21.3 ± 2.9	22.7 ± 3.3
278.9	30.1 ± 3.5	35.2 ± 3.5	42.3 ± 6.0	62.3 ± 9.6
296.7	19.0 ± 2.7	17.6 ± 2.3	18.6 ± 3.1	19.1 ± 3.8
296.7	21.6 ± 3.4	22.1 ± 3.3	23.9 ± 4.3	24.0 ± 4.8
316.2	15.1 ± 4.7	14.2 ± 4.0	18.8 ± 9.8	15.5 ± 11.1
348.1	13.2 ± 1.6	13.3 ± 1.6	13.6 ± 2.2	14.1 ± 3.4
351.9	12.1 ± 3.6	12.8 ± 3.6	34.8 ± 10.4	13.7 ± 8.4
ΔH_3, cal/mol	−2080 ± 360	−2240 ± 360		
ΔS_3, cal/(deg·mol)	−0.9 ± 1.2	−1.4 ± 1.2	*c*	*c*

[a] K_3 in M^{-1}. [b] Computer calculations did not converge for any estimate of K_3. [c] ΔH_3 and ΔS_3 not calculated. See text.

Table V. Comparison of Thermodynamic Quantities for Reaction 3 as a Function of Side Arm Chain Length

compd	n^a	K_3,^{b} M^{-1}	H_3, kcal/mol	ΔS_3, cal/(deg·mol)
5	4	8.26 ± 0.72	−2.73 ± 0.21	−4.9 ± 0.7
7	6	1.74 ± 0.36	−1.06 ± 0.28	−2.2 ± 0.8
8	8	20.1 ± 5.4	−2.16 ± 0.36	−1.2 ± 1.2

[a] Number of atoms in the side arm chain. [b] At 298 K.

progressive downfield shift of the four peaks of the pyridyl group and for the amide NH also of **7**, the equilibrium constants K_3 and limiting shifts δ_c were calculated. From the temperature dependence of K_3, ΔH_3 and ΔS_3 were calculated. The results are presented in detail in Table IV and summarized in Table V.

Figure 5 gives an example of the change in the visible spectrum of the false side arm zinc porphyrin, **10**, as a function of added 3-picoline. Table VI summarizes the equilibrium constants K_2 calculated for the two wavelengths 549 and 562 nm and the ΔH_2 and ΔS_2 values calculated from the temperature dependence of K_2 for the compounds **1**, **9**, and **10**. Table VII summarizes the best values of K_2(298 K), ΔH_2, and ΔS_2 for the compounds of this study and those reported previously, and Table VIII lists the derived values of K_1(298 K), ΔH_1, and ΔS_1 (see Discussion section).

Discussion

^{1}H NMR Spectra of Fully Coordinated Pyridyl Side Arm Porphyrins. The NMR spectra of all the zinc compounds of this study and their metal-free precursors are very solvent dependent, with major changes occurring in the shifts of the covalently attached pyridyl protons of **5**–**8** and in the coupling pattern and shifts of the pyrrole protons. The shifts of the pyridyl protons of compounds **5**–**8** are also temperature dependent, and in toluene they shift downfield about 0.002 (α'), 0.001 (α), 0.003 (β), and 0.004 (δ) ppm/deg as the temperature is increased while the pyrrole protons shift upfield about 0.001 ppm/deg. Both of these phenomena appear to be manisfestations of specific solvent interactions and not of aggregation effects, since previous NMR reports of aggregation of metallotetraphenylporphyrins[42,43] have shown that the pyrrole protons are shifted more than the phenyl protons, while in the present study it was found that the pyrrole-proton shift is less sensitive to change in solvent and temperature and is in the reverse direction to that of the pyridyl resonances. Since **5** obeys Beer's law over the concentration range 6.8×10^{-3} to 6.38×10^{-8} M and since aggregation of metallotetraphenylporphyrins has been shown to be least favorable in toluene of all common NMR solvents,[42] aggregation of the zinc side arm porphyrins of this study is unlikely.

The NMR shifts of the pyridyl protons of **4**–**8** in toluene at room temperature (Table I) vary as the length of the side arm varies in a manner which is probably indicative both of deviations of the $Zn-N_{py}$ axis from the desired perpendicular to the plane of the porphyrin nitrogens and of small changes in $Zn-N_{py}$ bond length

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(42) R. V. Snyder and G. N. LaMar, *J. Am. Chem. Soc.*, **99**, 7178 (1977).

(43) G. N. LaMar, J. DelGaudio, and J. S. Frye, *Biochim, Biophys. Acta*, **498**, 422 (1977).

Table VI. Equilibrium Constants, ΔH_2, and ΔS_2 Values for the Reaction in Toluene of 3-Picoline with a Series of Four-Coordinate Zinc Tetraphenylporphyrins

	K_2, M^{-1}	
T, K	λ 549 nm	λ 562 nm
	Compound **1**	
298.2	5320 ± 480	4790 ± 450
298.2	5120 ± 440	4180 ± 360
311.9	2180 ± 210	2590 ± 230
323.7	1630 ± 100	1550 ± 100
323.7	1540 ± 110	1270 ± 100
ΔH_2, kcal/mol	−8.81 ± 0.59	−8.60 ± 0.61
ΔS_2, cal/(deg·mol)	−12.7 ± 1.9	−12.2 ± 1.9
combined[a]	ΔH_2 = −8.71 ± 0.42 kcal/mol ΔS_2 = −12.4 ± 1.3 cal/(deg·mol)	
	Compound **9**	
298.2	8270 ± 650	9450 ± 760
298.5	9000 ± 770	9510 ± 830
311.5	4230 ± 350	4210 ± 350
311.9	4660 ± 370	4510 ± 350
323.7	2760 ± 180	2550 ± 180
ΔH_2, kcal/mol	−8.61 ± 0.66	−9.98 ± 0.69
ΔS_2, cal/(deg·mol)	−10.9 ± 2.1	−15.8 ± 2.2
combined[a]	ΔH_2 = −9.30 ± 0.48 kcal/mol ΔS_2 = −13.1 ± 1.5 cal/(deg·mol)	
	Compound **10**	
297.9	12 890 ± 630	11 040 ± 560
311.5	5 440 ± 220	5 730 ± 250
324.5	2 640 ± 90	2 910 ± 110
ΔH_2, kcal/mol	−11.50 ± 0.43	−9.74 ± 0.44
ΔS_2, cal/(deg·mol)	−19.8 ± 1.4	−14.1 ± 1.4
combined[a]	ΔH_2 = −10.63 ± 0.31 kcal/mol ΔS_2 = −17.0 ± 1.1 cal/(deg·mol)	
	Compound **11**	
298.6	28 600 ± 3600	35 400 ± 4700
298.6	27 900 ± 3900	25 700 ± 3600
311.9	13 200 ± 1200	13 500 ± 1200
324.0	6 780 ± 580	6 260 ± 530
ΔH_2, kcal/mol	−10.76 ± 0.95	−11.76 ± 0.89
ΔS_2, cal/(deg·mol)	−15.7 ± 3.0	−18.9 ± 2.8
combined[a]	ΔH_2 = −11.35 ± 0.67 kcal/mol ΔS_2 = −17.5 ± 2.1 cal/(deg·mol)	

[a] ΔH_2 and ΔS_2 calculated from least-squares fit of ln K_2 determined at both wavelengths.

and out-of-plane distance of the zinc atom, since all of these should affect the ring current felt by each of the four pyridyl protons. In particular, the switch in order of α' and α proton shifts on going from **5** to longer chain side arm compounds suggests that the plane of the pyridyl ring may be tipped around the Zn–N$_{py}$ axis such that the α' proton is closer to the porphyrin ring than is the α proton, and that the Zn–N$_{py}$ bond is stretched slightly (in comparison to **6**). The hypothesis of pyridyl ring tipping is borne out by the crystal structure of **5**,[18] which shows that the Zn–N axis is tipped about 1° toward the side arm attaching point which places the α' proton about 0.04 Å closer to the ring than the α proton.

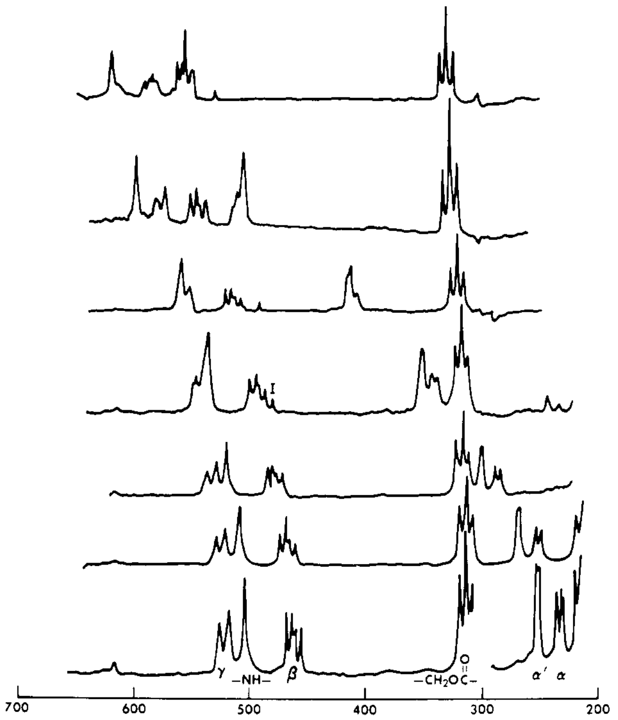

Figure 4. The 99.5-MHz ^{1}H NMR spectra of the pyridyl peaks of **7** in toluene-d_8 solution (bottom) as aliquots of 3-picoline are added.

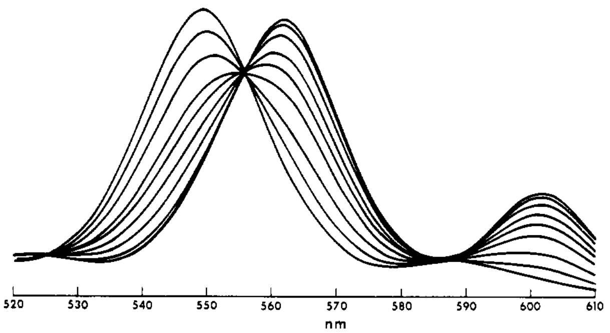

Figure 5. Visible spectra of **10** in toluene solution (λ_{max} 550, 588 nm) as aliquots of 3-picoline are added.

The Displacement Reaction (3). The equilibrium constants K_3 for the displacement of the covalently attached pyridyl of **5**, **7**, and **8** by 3-picoline in toluene-d_8 as a function of temperature were calculated from each of the four pyridyl proton shifts as a function of added free ligand (Table IV). A general feature of all sets of data is that the values of K_3 calculated from the shifts of the four pyridyl protons do not agree; the K_3 values calculated from the two α proton shifts generally agree fairly well with each other, while they differ from those calculated from β and γ pyridyl proton shifts which differ from each other. The K_3 values calculated from the amide proton shifts of **7** (Table IV) are even more divergent

Table VII. Summary of Equilibrium Constants, Enthalpies, and Entropies for the Base Addition Reaction (2) at 298 K

system	solvent	K_2, M^{-1}	ΔH_2, kcal/mol	ΔS_2, cal/(deg·mol)	ref
ZnTPP (**1**) + pyridine	cyclohexane	25 100	−10.00 ± 0.20	−13.5 ± 0.7	26
ZnTPP (**1**) + pyridine	chloroform	610	−4.0 ± 0.4	0 ± 3	23
ZnTPP (**1**) + pyridine	benzene	3 900	−8.8 ± 1.2	−13 ± 5	23
ZnTPP (**1**) + pyridine	benzene	4 800	−9.2	−14	21
ZnTPP (**1**) + pyridine	benzene	5 300			25
ZnTPP (**1**) + pyridine	benzene	6 030			22
ZnTPP (**1**) + pyridine	benzene	6 460			24
ZnTPP (**1**) + 3-picoline	toluene	4 530	−8.7 ± 0.4	−12.4 ± 1.3	this work
ZnTPP acetamide (**9**) + 3-picoline	toluene	8 840	−9.3 ± 0.5	−13.1 ± 1.5	this work
ZnTPP false side arm (**10**) + 3-picoline	toluene	12 000	−10.6 ± 0.3	−17.0 ± 1.0	this work
ZnTPP double false side arm (**11**) + 3-picoline	toluene	29 400	−11.3 ± 0.7	−17.5 ± 2.1	this work

Table VIII. Derived Thermodynamic Quantities for the Off-On Equilibrium of Zinc Side Arm Porphyrins

compd	n_{SB}[a]	K_1[b]	ΔH_1, kcal/mol[c]	ΔS_1, cal/(deg·mol)[c]	$\Delta S_1/n_{SB}$
5	3	1450	−7.9	−12.1	−4.0
7	5	6900	−9.5	−14.8	−3.0
8	7	600	−8.4	−15.8	−2.3
	compare with the reaction of 3-picoline with				
10		$K_2 \times 1M$	−10.6	−17.0	

[a] n_{SB} = number of single bonds which can undergo free rotation when the pyridyl side arm is uncoordinated (see text). [b] At 298 K, $K_1 = K_2/K_3$. [c] $\Delta H = \Delta H_2 - \Delta H_3$, $\Delta S_1 = \Delta S_2 - \Delta S_3$, where the data for reaction 2 are those of compound **10**.

from the values calculated from the pyridyl proton shifts. Since the β and γ protons of the coordinated pyridyl and the NH of the side arm are more accessible to solvent, and since the total shifts experienced by these protons are smaller than those of the two α protons, the values of K_3 calculated from the shifts of these protons are more subject to extraneous factors. This could explain why the results obtained from these protons are not consistent with those of the α protons. Because the results obtained from the α protons of the side arm pyridyl were consistent with each other, only these results will be considered further.

Examination of the calculated limiting complexed shifts of the pyridyl protons did not show any unexpected results. The calculated limiting shifts for duplicate runs generally agree within their respective standard deviations. The calculated shifts of the two α protons are similar, and both are downfield from the β and γ protons which are close to each other, a pattern similar to that of the shifts of 3-picoline in toluene (α, α', 8.33; β, 6.68; δ, 6.91 ppm). As the side arm becomes longer, the calculated limiting shifts more closely approach the free 3-picoline values, indicating that the limiting complexed shifts of the pyridyl protons of the longer side arm compounds are less affected by the porphyrin ring current than are those of the shorter side arm compounds.

For all of the pyridyl arm compounds studied, the covalently attached pyridyl is strongly coordinated to the central zinc. At room temperature, it is more difficult, in terms of equilibrium constant (free energy), to displace the pyridyl ligand of **7**, less difficult to displace that of **5**, and least difficult to displace that of **8** (Table V). Examination of molecular models (CPK) suggests that there is slightly more strain in the chain of the coordinated side arm of **5** than of **7**, and the calculated enthalpies of displacement of the pyridyl ligand appear to reflect this. Less can be said about strain in the chain of compound **8**, because of the increased number of possible rotations. Several measurements of K_3 for the reaction of compound **5** with 3-picoline and pyridine were also carried out in benzene-d_6 solution at room temperature. For 3-picoline, the average value of K_3 is 7.75 M^{-1}, within the experimental error of the value (8.26 M^{-1}) obtained in toluene-d_8 solution, suggesting that solvent effects are similar in the two solvents. For pyridine, the average value of K_3 is 6.9 M^{-1} in benzene, reflecting the lower basicity of the competing base in this case.

In all cases, the equilibrium constant for displacement of the side arm pyridyl by external base, K_3, is greater than 1.0 M^{-1} over the temperature range of these measurements (Table IV), indicating that at a concentration of 1 M the free ligand forms a more stable complex with ZnTPP than do any of the covalently attached pyridyl ligands. The origin of this stability appears to be in part enthalpic and in part entropic, with solvation playing an important role in each term. Looking first at the enthalpy for displacement of the covalently attached pyridyl (summarized in Table V), we note that ΔH_3 is always negative. That is, 3-picoline appears to form a stronger bond with zinc than do any of the covalently attached pyridyls. Part of this difference, especially for compound **5**, is caused by the short connecting chain. In addition, however, from arguments to be presented below, we feel that nearly 2 kcal/mol of ΔH_3 is due to the difference in solvation between the side arm pyridyl complexes and ZnTPP. To develop and explain this argument further, studies of reaction 2 were carried out on compounds having various noncoordinating groups attached to the ortho position of one of the phenyl rings of ZnTPP. We now turn to a discussion of the results of those studies.

The Free Ligand Addition Reaction (2). Numerous studies of ligand addition to ZnTPP and its tetra-*p*-phenyl substituted derivatives have been reported,[22,27,34] but in no case was toluene the solvent used. Therefore, in order to relate this work to previously reported studies, K_2 was determined for ZnTPP, **1**, and 3-picoline in toluene as a function of temperature. To determine the electronic effect of a side chain amide group, the same reaction was studied for the *o*-acetamide compound **9**; to determine the effect of an uncoordinated side arm on the thermodynamics of 3-picoline addition, the false side arm, compound **10**, and double false side arm, compound **11**, were studied. The values of K_2 were calculated at two wavelengths as a function of temperature for compounds **1**, **9**, **10**, and **11** (Table VI). The values obtained at the two wavelengths generally agree within one standard deviation with no consistent pattern in the deviations observed. Therefore, ΔH_2 and ΔS_2 summarized in Table VII are calculated from the combined data for the two wavelengths, and from these data the least-squares average K_2 in toluene at 298 K for each compound are also presented together with representative data from the literature for related addition reactions in various solvents.

Before considering the data of this work, the available literature data for the reaction of ZnTPP (**1**) with pyridine must be considered. For benzene as solvent, K_2 varies from 3900 to 6460 M^{-1} depending on investigator (Table VII). The 3900 M^{-1} value is probably less reliable than the others because of the widely fluctuating values of ΔS_2 reported in that study,[23] while the other values reported for this system probably agree within experimental error.

Comparison of the values of K_2 for ZnTPP (**1**) plus pyridine in benzene[21,22,25] with the value obtained in cyclohexane[26] shows that benzene seriously interferes with the addition of pyridine to ZnTPP (K_2 is about five times larger when the solvent is cyclohexane) and that this interference is largely, if not entirely, due to the enthalpy term. The enthalpy, ΔH_2, is the sum of two terms:

$$\Delta H_2 = \Delta H_f(\text{Zn–N bond}) + \Delta H(\text{solvent effects}) \quad (5)$$

If we assume that cyclohexane is a noninteracting solvent,[26] then ΔH_f(Zn–N bond) can be approximated by ΔH_2 in cyclohexane, or $\Delta H_f = -10$ kcal/mol. The solvent-effect contribution to ΔH_2 in (5) arises from several sources. First, there is that due to solvation of the porphyrin. Vogel and Stahlbush[26] have estimated ΔH of solvation of ZnTPP (**1**) by one benzene molecule to be −1.4 kcal/mol. Although the crystal structure of the toluene solvate[44] shows one aromatic solvent molecule on each side of the ZnTPP, only one of these must be removed in order to form the five-coordinate adduct. Since benzene is a weak π donor,[45,46] the remaining benzene will probably decrease the Lewis acidity of zinc by increasing the porphyrin π electron density as it solvates the π system. The ΔH for this effect is hard to estimate but is surely less than that for solvent removal, perhaps 0–0.4 kcal/mol. The total contribution to ΔH due to solvent effects is thus on the order of 1.4–1.8 kcal/mol. From (5), the ΔH_2 in benzene should be −8.6 to −8.2 kcal/mol, which is in fair agreement with the value of −9.2 kcal/mol reported by Miller and Dorough.[21] Assuming that it is totally an enthalpy effect, the difference in K_2 for pyridine or 3-picoline addition of ZnTPP in benzene[22] leads to a difference of only 0.04 kcal/mol in ΔH_2. Using the relationship derived by Vogel and Stahlbush[26] between the position of the Soret band of ZnTPP in cyclohexane and the red shift when various solutes are added, we obtain the same value for ΔH in toluene as in benzene. Thus, the values for ΔH obtained for the reactions of ZnTPP + pyridine in benzene and of ZnTPP + 3-picoline in toluene should be the same. From Table VII, one can see that within experi-

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[44] W. R. Scheidt, M. E. Kastner, and K. Hatano, *Inorg. Chem.*, **17**, 706 (1978).

[45] O. W. Kolling, *Inorg. Chem.*, **18**, 1175 (1979).

[46] M. J. Kamlet, J. L. Abboud, and R. W. Taft, *J. Am. Chem. Soc.*, **99**, 6027 (1977).

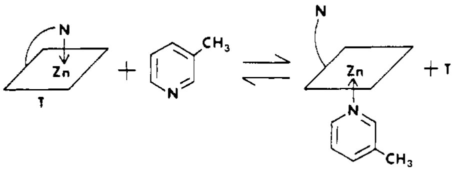
mental error they are in good agreement with the ΔH estimated above.

If the data for ZnTPP acetamide (**9**) reacting with 3-picoline are next considered, it should be noted that ΔH_2 is more negative for this reaction, suggesting a substituent effect of the side arm amide group. This substituent effect is also evident in comparing the ΔH_2 values for the false side arm (**10**) and the double false side arm (**11**) reactions with 3-picoline. The effect of the side arm amide appears to be to cause ΔH_2 to be more negative by about 0.6–0.7 kcal/mol. If this is a substituent effect, then the side arm amide group in the ortho position of one phenyl ring has a significant electron-withdrawing effect in distinction to its expected negligible substituent effect based on its reported para σ constant of 0.00.[47] Because of its proximity to the porphyrin π system, its π orbital may overlap directly with the porphyrin π system, thus allowing a larger than expected electronic effect for this substituent. That there is direct overlap between amide and prophyrin π orbitals is also suggested by electrochemical studies of the zinc side arm porphyrins: every ZnTPP derivative having an ortho amide shows a third oxidation reaction (in addition to π cation radical and dication formation).[48] In methylene chloride, this third oxidation occurs at about +1.4 V vs. SCE.

The similarity in ΔS_2 for addition of 3-picoline to the false (**10**) and double false (**11**) side arm complexes of ZnTPP together with the larger difference in ΔS_2 for the same reaction of ZnTPP acetamide (**9**) and the 1.3 kcal/mol difference in ΔH_2 between **9** and **10** suggest that the nature of the reaction between 3-picoline and zinc is fundamentally different for **10** and **11** than it is for **1** and **9**. The similarity in ΔS_2 for **10** and **11** suggests that 3-picoline may add to the axial position of zinc which is on the same side of the porphyrin plane as is the false side arm of compound **10**. Thus, ΔS_2 should differ for **10** and **11** by $R \ln 2$ or 1.4 cal/(deg·mol) with ΔS_2 for **10** being more negative than for **11**. This is not the direction of the observed difference in ΔS_2 for these two compounds, but the experimental error in ΔS_2 is large enough to mask the expected trend.

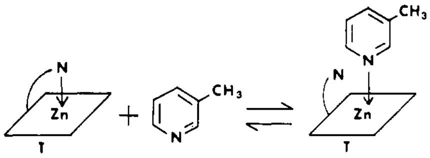
If 3-picoline adds to the axial position of zinc on the same side of the porphyrin ring as the false side arm for compound **10** as well as **11**, then the difference in ΔH_2 between the acetamide (**9**) and mono false side arm (**10**) derivatives of ZnTPP must be due to differences in solvation of the porphyrin. This suggests that there is no toluene of solvation π complexed on the side of the porphyrin plane which carries the false side arm, which apparently undergoes enough thermal motion to prevent a solvent molecule from forming a well-defined π complex to the porphyrin ring. This is interesting in light of the recently reported study of oxygen binding to the "picket fence" derivative of CoTPP·B,[49] where it was concluded that the reason that the picket fence porphyrin binds O_2 more readily than simple tetraphenylporphyrin derivatives is that the four trimethylacetamide "pickets" prevent toluene from solvating the porphyrin ring at the site where oxygen it to bind, whereas for the simple tetraphenylporphyrins[50] a toluene of solvation must be removed in order for O_2 to bind. The present work also suggests that one bulky substituent on the ortho position of one phenyl ring does not prevent binding of ligand to the metal on the side of the porphyrin plane which carries the substituent but does prevent toluene solvation at that site. The measured ΔS_2 for reaction of 3-picoline with **10** and **11** is thus the balance between loss of entropy by 3-picoline (~−40 cal/(deg·mol) in solution)[51] and the gain in entropy of the solvent as a whole, in part from removal of solvent from the vicinity of the coordination site and in part from removal of solvent from 3-picoline. The fact that these changes in ΔS of solvation (ΔS_{solv} = 40 cal/(deg·mol) + ΔS_2, or ~23 cal/(deg·mol)) are somewhat smaller than those of ZnTPP acetamide (**9**) and ZnTPP (**1**) (~27–28 cal/(deg·mol)) is in line with the hypothesis of less specific solvation of the coordination site of **10** and **11**. Interestingly, the entropy gained by cyclohexane when ZnTPP reacts with pyridine in this solvent[26] is the same as observed in this work for toluene as solvent, which suggests that cyclohexane also solvates the porphyrin plane in the vicinity of the axial position of zinc, and thus cyclohexane is not a truly noninteracting solvent.

Derivation of Thermodynamic Quantities for the Off–On Reaction (1). The information obtained from investigation of reaction 2 raises certain implications concerning the derivation of values of K_1, ΔH_1, and ΔS_1, with regard to the side of the plane of the side arm pyridyl porphyrins to which 3-picoline binds and the involvement of toluene in specific solvation of the porphyrin in the vicinity of the zinc coordination site. If 3-picoline binds to the opposite side of the plane, as was suggested by the way in which reaction 3 was written above, then reaction 3 should be written as (6), where T represents a toluene molecule which interacts



(6)

specifically at the sixth position of the side arm porphyrin when the side arm is coordinated but not when 3-picoline is coordinated based upon the conclusions reached above concerning solvation of the false **10** and double false **11** side arm porphyrins. If one now notes that the product of reaction 6 has no toluene of solvation opposite the bound 3-picoline, it seems entirely plausible that a free 3-picoline in the solution might react with this 3-picoline-coordinated pyridyl side arm zinc porphyrin to displace the first 3-picoline and bind to the unsolvated side of the molecule. That is, by considering the enthalpies of reactants and products of reactions 6 and 7 below, and based on the results reported herein for addition of 3-picoline to compounds **9** and **10**, the thermodynamics of displacement of the side arm pyridyl by 3-picoline are more favorable if, at equilibrium, 3-picoline binds to the same side of the porphyrin plane as carries the side arm pyridyl. Thus, although it may occur in two very rapid steps, reaction 3 is probably best written as (7). Combination of thermodynamic



(7)

data for reaction 7, which was previously called reaction 3, with that for reaction 2 should thus yield thermodynamic data for reaction 1. The derived values of ΔH_1, ΔS_1, and K_1 at 25 °C are presented in Table VIII together with the data for reaction 2 between 3-picoline and the false side arm compound **10**. Comparison is made to compound **10** rather than **9** because **10** apparently does not lose a toluene of solvation, while **9** does when 3-picoline binds; as thus derived, reaction 1 does not involve loss of toluene of solvation.

Looking first at the enthalpies of the off–on reaction (1) as a function of chain length in comparison to the simple addition reaction (2), it is clear that all of the side arm porphyrins studied here are strained to some extent, compound **7** being the least strained. Interestingly, this strain, at least for compound **5**, manifests itself not in stretching of the Zn–N_{py} bond length or Zn out-of-plane distance, but rather in distortion of the angles among the atoms of the side chain and other molecular deformations.[18] The entropy of the off–on reaction (1) varies with the length of the chain connecting the pyridyl to the phenyl ring of ZnTPP and appears to represent contributions from internal rotations about each single bond of the side arm chain. To count the number of single bonds which can undergo free rotation when the side arm pyridyl is uncoordinated, it seems reasonable to

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exclude the amide bond, which is known to have considerable double bond character and marked hindrance to rotation,[52] and also to exclude the phenyl–N bond, which is expected to be hindered by the porphyrin ring from carrying out free rotation. Thus, "n_{SB}" in Table VIII, the number of single bonds which can carry out free rotations in the uncoordinated side arm chain, has been adjusted for these considerations. The last column of that table gives the contribution to ΔS_1 for each of these single bonds in the side arm. This incremental ΔS per internal rotation is within the range (3–5 cal/(deg·mol)) found for cyclization of olefins and other reactions in which such internal rotations play an important role in the observed entropy of activation or reaction.[51,53] It decreases as the chain becomes longer since the coordinated pyridyl's connecting chain can undergo partial internal rotation as the chain lengthens, also consistent with results from other systems.[51,53] It is interesting but probably fortuitous that the entropy of internal rotation lost by the side arm pyridyl on coordination is so similar to the balance of the translational and rotational entropies lost by the free 3-picoline ligand on binding to zinc and the entropy gained by the solvent upon 3-picoline binding. Since this balance appears to be fairly independent of solvent (cyclohexane, $\Delta S_2 = -13.5$ cal/(deg·mol);[26] benzene, $\Delta S_2 = -13$ to -14 cal/(deg·mol);[21,23] toluene, $\Delta S_2 = -12$ to -13 cal/(deg·mol)), it appears unlikely that any side arm liganded metalloporphyrin will form a stable axial complex with its metal in solution nor would the same metalloporphyrin with a free ligand of analogous structure. However, the advantage of using side arm metalloporphyrins remains that coordination geometry may be controlled and that excess uncoordinated ligands need not be present in the solution.[54]

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Catalysis by Multimetallics. Catalyzed Homogeneous Oxidation of Alcohols and Ketones with Molecular Oxygen in the Presence of Hexarhodium Hexadecacarbonyl and Dirhenium Decacarbonyl

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Abstract: The compounds $Rh_6(CO)_{16}$ and $Re_2(CO)_{10}$ are effective catalysts for the conversion of ketones and cyclic alcohols to carboxylic acids. Cyclohexanol is converted to adipic acid via cyclohexanone as intermediate. Temperature, solvent, and pressure effects are reported and discussed. Increased acid yield with $Rh_6(CO)_{16}$ under conditions of increased CO and decreased oxygen pressure are interpreted on the basis of a lower nuclearity rhodium carbonyl being the reactive intermediate. The catalytic effect of the metal carbonyl is a consequence of the accelerated decomposition of the preformed peroxide intermediates. The side product ϵ-caprolactone is formed in the oxidation of cyclohexanone, but the yield is decreased in the presence of $Rh_6(CO)_{16}$ because of the catalyzed decomposition of its precursor peracid. The metal carbonyls catalyze the decomposition of hydrogen peroxide, but unlike ferrous ion (Fenton's reagent) do not enhance its function as an organic oxidant.

In earlier publications we described the use of the complex $Rh_6(CO)_{16}$ as a homogeneous catalyst for the oxidation, with molecular oxygen, of carbon monoxide to carbon dioxide and of ketones to carboxylic acids.[1] In that work we concluded that the oxidation of ketones was a free-radical process, but the role of the transition metal carbonyl complex was not identified. In these earlier studies we found that the compounds $Pt(PPh_3)_3$ and $IrCl(CO)(PPh_3)_2$ were also effective for increasing the yields of carboxylic acids from ketones under autoxidation conditions. The purpose of this paper is to focus interest in catalysis by clusters and to identify the role of the transition metal carbonyl in this reaction. Furthermore, we will present and discuss our new discoveries on alcohol autoxidation and the use of dirhenium decacarbonyl as an oxidation catalyst.

Two roles appear to have been identified for metal complexes in oxidations with molecular oxygen. The first is the coordination and activation of molecular oxygen.[2] This role has been claimed in the conversion of phosphines to phosphine oxides,[3] alkenes to ketones,[4] CO to CO_2,[5] alkenes to epoxides,[6] and isocyanides to

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