

## The Nuclear Magnetic Resonance Spectra of Porphyrins. Part X.<sup>1</sup> Carbon-13 Nuclear Magnetic Resonance Spectra of Some *meso*-Tetra- arylporphyrins and their Metal Chelates

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The <sup>13</sup>C n.m.r. spectra of *meso*-tetraphenylporphyrin (TPP), the zinc(II), cadmium(II), bis[mercury(II) acetate], and various thallium(III) derivatives, and some related analogues are reported and assigned. In *meso*-tetra-(*o*-tolyl)-porphyrin and *meso*-tetra-(1-naphthyl)porphyrin only one species was observed. The introduction of zinc(II), cadmium(II), or bis[mercury(II) acetate] into the TPP nucleus does not significantly change the <sup>13</sup>C shifts, but the thallium(III) derivative shows both extensive Tl-<sup>13</sup>C couplings and non-equivalence of *o*-phenyl carbon atoms, the latter being due to the exoplanar position of the thallium atom. Specific Tl-<sup>13</sup>C couplings to the *o*-phenyl carbon atoms are also observed.

The phenomenon of slow protonation (TPP  $\rightleftharpoons$  TPPH<sub>2</sub><sup>2+</sup>) was identified and examined by using <sup>13</sup>C and <sup>1</sup>H n.m.r. spectroscopy, and the <sup>13</sup>C shifts and assignments for the dication are reported. The large protonation shifts of TPP and high  $\Delta G^\ddagger$  value for this process (*ca.* 16.3 kcal mol<sup>-1</sup>) are consistent with the further buckling of the macrocycle on protonation, due to decrease in the angle between the macrocycle and the phenyl rings. In contrast, the protonation shifts of *meso*-tetra-(*o*-tolyl)porphyrin are 'normal' owing to the additional steric requirements of the *o*-methyl groups. A hitherto unrecorded effect is the shift of the tetramethylsilane reference in trifluoroacetic acid compared with deuteriochloroform of 1.5 p.p.m. upfield with respect to other reference compounds.

Identification of the coalescence temperature for the NH tautomerism in both the <sup>13</sup>C and <sup>1</sup>H spectra allows the kinetic parameters for this process to be determined ( $\Delta G^\ddagger_{303}$  *ca.* 12.3 kcal mol<sup>-1</sup>,  $\Delta H^\ddagger$  *ca.* 9.2 kcal mol<sup>-1</sup>, and  $\Delta S^\ddagger$  *ca.* -10 cal K<sup>-1</sup> mol<sup>-1</sup>). These, and the isotope effect ( $k_{NH}/k_{ND}$ ) of *ca.* 12 (measured at one temperature to remove entropy of activation effects) are consistent with a two-step (rather than a concerted) process.

SPECTROSCOPIC studies of the porphyrin macrocycle and its diverse derivatives are of continuing and current interest because of the biological importance of this class of compound<sup>2</sup> as well as the fundamentally intriguing properties of the highly conjugated macrocycle. We are particularly interested in the determination of the advantages and limitations of <sup>13</sup>C n.m.r. spectroscopy in this field. Previous publications in this Series have reported<sup>3</sup> detailed assignments of the <sup>13</sup>C spectra of some peripherally substituted porphyrins and have shown that these shifts, together with other evidence, provide conclusive evidence for the delocalisation pathway in these molecules. Line broadening of the 'α-pyrrole' resonances was observed and

<sup>1</sup> Part IX, K. M. Smith and J. F. Unsworth, *Tetrahedron*, in the press.

<sup>2</sup> H. Fischer and H. Orth, 'Die Chemie des Pyrrols,' Akademische Verlag, Leipzig, vols. I, Iii, and Iii, 1934—1940.

ascribed to NH tautomerism, and this was supported by the absence of this effect in diprotonated and metal derivatives. These studies were extended<sup>1</sup> to the important chlorophyll degradation products, detailed assignments for which were a necessary preliminary for biosynthetic studies using <sup>13</sup>C labelling.

The present investigation extends this analysis to porphyrins substituted at four *meso*-positions and to some of their metal complexes, with particular reference to atropisomerism, slow protonation, and NH tautomerism. Part of this work has been the subject of preliminary publications.<sup>4,5</sup>

<sup>3</sup> R. J. Abraham, G. E. Hawkes, and K. M. Smith, *J.C.S. Chem. Comm.*, 1973, 401; *J.C.S. Perkin II*, 1974, 627.

<sup>4</sup> R. J. Abraham, G. E. Hawkes, and K. M. Smith, *Tetrahedron Letters*, 1974, 71.

<sup>5</sup> R. J. Abraham, G. E. Hawkes, and K. M. Smith, *Tetrahedron Letters*, 1974, 1483.

## RESULTS AND DISCUSSION

The  $^{13}\text{C}$  chemical shifts and assignments for all porphyrins investigated are collected in Table 1. In the spectra of *meso*-tetraphenylporphyrin (I) (TPP),

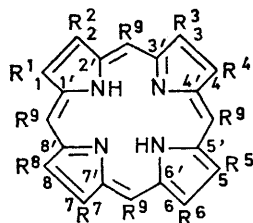
while the ' $\beta$ -pyrrole' carbon signals (1—8) are considerably broadened upon replacement of the 'inner' protons with deuterons.<sup>3-5</sup> This latter effect arises from the isotope effect upon the rate of NH tautomerism

TABLE 1  
 $^{13}\text{C}$  Chemical shifts <sup>a</sup> of some porphyrins, dications, and metalloporphyrins

	Nuclear carbon atoms			Substituent carbon atoms					
	C <sub><math>\alpha</math></sub>	C <sub><math>\beta</math></sub>	C <sub><i>meso</i></sub>	C-1''	C-2''	C-3''	C-4''	C-5''	C-6'
TPP (35°)	145.8 <sup>b</sup>	130.6	119.6	141.7	134.0	126.1	127.5		
TPP (-60°)	137.1	127.0	119.5	141.0	133.9	126.1	127.3		
Zn <sup>II</sup> TPP <sup>b</sup>	150.8	132.5	121.6	143.3	134.9	127.5	128.0		
Cd <sup>II</sup> TPP <sup>c</sup>	150.2	131.1	121.0	143.5	134.3	125.7	126.5		
Tl <sup>III</sup> TPP <sup>d</sup>	149.3	132.2	121.8	141.3	134.6	126.4	127.6		
(OH, H <sub>2</sub> O)	(13)	(119)	(141)	(24)	(19)				
					133.9				
					(20)				
Tl <sup>III</sup> TPP <sup>e</sup>	149.4	132.2	<i>i</i>	141.2	134.6	126.3	127.5		
(OH, H <sub>2</sub> O)	(13.5)	(119.2)		(25.1)	(19.6)				
					133.9				
					(20.1)				
Tl <sup>III</sup> TPP	149.3	131.8	121.6	141.1	134.6	126.1	127.3		
(OAc, H <sub>2</sub> O)	(17)	(120)	(147)	(27)	(18)				
					133.8				
					(22)				
Tl <sup>III</sup> TPP	149.3	132.1	121.6	141.1	134.4	126.3	127.5		
(CN)	(7.0)	(110)	(115)	(17)	(20)				
					133.8				
					(13)				
TPP(HgOAc) <sub>2</sub>	152.4	132.1	123.5	141.7	134.6	126.4	127.5	(19.2; CO·CH <sub>3</sub> )	
(TPPH <sub>2</sub> ) <sup>2+</sup> <sup>f</sup>	145.2	127.7	122.1	139.4	137.9	127.7	129.4		
(TPPH <sub>2</sub> ) <sup>2+</sup> <sup>g</sup>	147.3	131.0	123.9	140.1	139.5	130.1	132.5		
TOP	146.0 <sup>b</sup>	130.3	118.4	139.1	141.0	127.9	128.8	123.7	133.5
								(21.3; <i>o</i> -Me)	
Tl <sup>III</sup> TOP	149.2	131.5	<i>i</i>	138.6 <sup>*</sup>	140.8 <sup>*</sup>	128.0	128.7	123.7	133.8
(OH, H <sub>2</sub> O)	(21)	(116)		(17)	(26)				(25)
					139.9 <sup>*</sup>				133.0
					(17)				(17)
								(21.0; <i>o</i> -Me)	
(TOPH <sub>2</sub> ) <sup>2+</sup> <sup>f</sup>	145.0	129.7	120.6	138.4	140.6	127.9	128.1	124.6	135.7
								(21.0; <i>o</i> -Me)	
(TOPH <sub>2</sub> ) <sup>2+</sup> <sup>g</sup>	147.3	131.5 <sup>*</sup>	124.0	139.1	142.1	131.7 <sup>*</sup>	132.5	126.8	137.8
								(21.6; <i>o</i> -Me)	
TNP	147.3 <sup>b</sup>	130.5	117.1	138.4	132.1	123.5	127.1 <sup>*</sup>	128.0 <sup>*</sup>	125.0 <sup>†</sup>
					125.6 <sup>†</sup> (7''), 128.0 <sup>*</sup> (8''), 136.0 (9''), 132.1 (10'').				

<sup>a</sup> Solutions in CDCl<sub>3</sub>, unless otherwise stated. Chemical shifts in p.p.m. downfield from internal Me<sub>4</sub>Si ( $\pm 0.1$  p.p.m.). Values in parentheses beside chemical shifts are assignments, and those beneath are Tl- $^{13}\text{C}$  coupling constants in Hz ( $\pm 2$  Hz). Assignments marked  $\dagger$  or  $*$  may be interchanged. <sup>b</sup> Chemical shifts from ref. 9. <sup>c</sup> In presence of *ca.* 2 equiv. of pyrrolidine. <sup>d, e</sup>  $^{13}\text{C}$  spectra at 25.2 and 15.1 MHz, respectively. <sup>f, g</sup> Solutions in CDCl<sub>3</sub> and TFA, respectively. <sup>b</sup> Broad (25—50 Hz) weak signals. <sup>†</sup> Only high-field half of doublet observed.

*meso*-tetra-(*o*-tolyl)porphyrin (II) (TOP), and *meso*-tetra-(1-naphthyl)porphyrin (III) (TNP) the resonances



- (I) TPP, R<sup>1-8</sup> = H, R<sup>9</sup> = Ph  
 (II) TOP, R<sup>1-8</sup> = H, R<sup>9</sup> = *o*-MeC<sub>6</sub>H<sub>4</sub>  
 (III) TNP, R<sup>1-8</sup> = H, R<sup>9</sup> = 1-naphthyl  
 Deutero-IX, R<sup>1,3,5,8</sup> = Me, R<sup>2,4,9</sup> = H, R<sup>6,7</sup> = P  
 Copro-I, R<sup>1,3,5,7</sup> = Me, R<sup>2,4,6,8</sup> = P, R<sup>9</sup> = H  
 P = CH<sub>2</sub>·CH<sub>2</sub>·CO<sub>2</sub>Me

of the ' $\alpha$ -pyrrole' type carbons (1'—8') are readily identified as the broad, weak signal to lower field,<sup>3-5</sup>

in the porphyrin (see later). The signals of the phenyl ring carbons of TPP were assigned with the aid of single frequency off-resonance  $^1\text{H}$  decoupling (SFORD) to distinguish the quaternary (C-1'') carbons and the *meso*-carbons. The  $^{13}\text{C}$  shifts of C-1'' and the *para*-carbons (relatively low signal intensity) are very similar to the corresponding shifts in biphenyl<sup>6</sup> (141.7 and 127.7 p.p.m., respectively). For biphenyl the *meta*-carbon signals were assigned to lower field than the *ortho*-carbon signals, but for TPP, the lower field signal of the two remaining methine carbon resonances is assigned to the *ortho*-carbon, in order to be consistent with the assignments for the thallium(III) chelate (see later). The remaining quaternary carbon signal (119.6 p.p.m.) is assigned to that in the *meso*-position.

<sup>6</sup> T. D. Alger, D. M. Grant, and E. G. Paul, *J. Amer. Chem. Soc.*, 1966, **88**, 5397; see also J. B. Stothers, 'Carbon-13 NMR Spectroscopy,' Academic Press, London, 1972, ch. 3.

For TOP, where four atropisomers are possible<sup>7</sup> owing to restricted rotation about the phenyl-porphyrin ring bonds, only *one* set of <sup>13</sup>C resonances was observed. The porphyrin ring carbon signals,  $\alpha$ - and  $\beta$ -'pyrrole' types and *meso*, were assigned as for TPP. The basis for the assignment of the tolyl ring carbon signals was comparison with the phenyl ring assignments for TPP with consideration of the <sup>13</sup>C substituent shifts found by Woolfenden and Grant<sup>8</sup> for the substitution toluene  $\rightarrow$  *o*-xylene, where a positive value for  $\Delta\delta$  indicates the xylene resonance at lower field. Thus, the assignments for TOP were made by comparison of observed and predicted shifts (Figure 1; the values in parentheses are predicted shifts).

In the <sup>13</sup>C spectrum of TNP, in spite of the possibility of atropisomerism<sup>7</sup> as for TOP, only one set of resonances was observed (twelve signals out of thirteen were

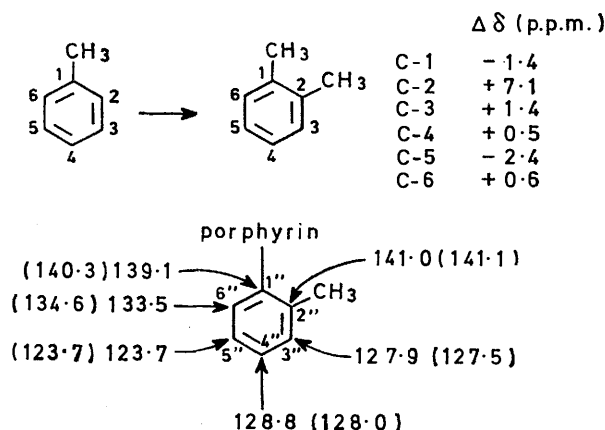


FIGURE 1

actually resolved). By comparison with the spectra of TPP and TOP, the signals at 147.3, 130.5, and 117.1 p.p.m. were immediately assigned to the  $\alpha$ - and  $\beta$ -'pyrrole' type and *meso*-carbons, respectively, of the macrocycle. Of the remaining resonances, those at 138.4, 136.0, and 132.1 p.p.m. were identified as being due to quaternary carbons (SFORD). In view of the paucity of published data on the <sup>13</sup>C n.m.r. spectra of substituted naphthalenes, the following assignments for the naphthalene ring carbons must be considered to be tentative. The <sup>13</sup>C substituent-induced shifts upon substitution of the porphyrin ring in the benzene ring are as shown in Figure 2 for TPP (*cf.* benzene<sup>6</sup>) and TOP (*cf.* toluene<sup>6,8</sup>); a positive value indicates the signal from the porphyrin derivative at lower field. Applying the substituent parameters from the TOP-toluene comparison to the published<sup>6</sup> <sup>13</sup>C shifts for naphthalene (C-1 at 128.3, C-2 at 126.1, C-9 at 133.9 p.p.m.) yields the correlation shown in Figure 3 between observed and predicted (in parentheses) shifts. Here the porphyrin substituent has been proposed to have a

\* Owing to insufficient signal : noise ratio, we did not observe the expected <sup>119</sup>Hg-<sup>13</sup>C satellites.

† No differentiation between <sup>203</sup>Tl-<sup>13</sup>C and <sup>205</sup>Tl-<sup>13</sup>C splittings was observed, and we follow previous practice<sup>3</sup> in referring to these as Tl-<sup>13</sup>C couplings.

minimum effect upon the <sup>13</sup>C shifts of carbons 5'', 6'', 7'', and 8''.

The <sup>13</sup>C chemical shifts and assignments of some metalloporphyrins are also shown in Table 1. The

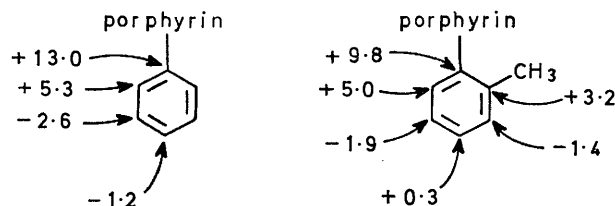


FIGURE 2

values for the <sup>13</sup>C shifts of Zn<sup>II</sup>TPP are those of Wüthrich and Baumann.<sup>9</sup> As found previously<sup>3</sup> for the coproporphyrins, <sup>13</sup>C shifts of a diamagnetic metalloporphyrin are very similar to those of the parent porphyrin. With this assistance, the aid of SFORD spectra, and the observation that, of the methine carbon resonances for the TPP derivatives, the *para*-carbon signals are of reduced intensity, the assignments of Zn<sup>II</sup>TPP, Cd<sup>II</sup>TPP, and (Hg<sup>II</sup>OAc)<sub>2</sub>TPP\* follow directly. The <sup>13</sup>C spectrum of Cd<sup>II</sup>TPP was run in the presence of *ca.* 2 equiv. of pyrrolidine to increase solubility. It is reasonable to assume that the added base does not significantly perturb the <sup>13</sup>C shifts since Wüthrich and Baumann<sup>9</sup> noted very little difference between the <sup>13</sup>C spectra of Zn<sup>II</sup>TPP in [2H<sub>5</sub>]pyridine and CDCl<sub>3</sub> solutions.

The <sup>13</sup>C spectrum (<sup>1</sup>H noise-decoupled) of Tl<sup>III</sup>TPP(OH) was considerably more complex than those of the metalloporphyrins discussed above. In addition to extensive Tl-<sup>13</sup>C coupling † a greater number of lines than expected was observed in the 133–135 p.p.m. region of the spectrum. Accordingly, the spectrum was analysed in terms of asymmetry induced by the metal lying out of the plane of the porphyrin ring, and restricted rotation about the phenyl-porphyrin ring

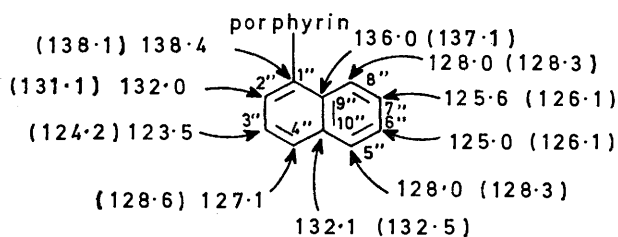


FIGURE 3

bond (below *ca.* 60°) (Figure 4). In this context, it is also of interest that recent calculations<sup>10</sup> have shown that in solution the macrocycle and phenyl rings are slightly more coplanar than in the solid state.

<sup>7</sup> F. A. Walker and G. L. Avery, *Tetrahedron Letters*, 1971, 4949; L. K. Gottwald and E. F. Ullman, *ibid.*, 1969, 3071.

<sup>8</sup> W. R. Woolfenden and D. M. Grant, *J. Amer. Chem. Soc.*, 1966, **88**, 1496.

<sup>9</sup> K. Wüthrich and R. Baumann, *Helv. Chim. Acta*, 1973, **56**, 585.

<sup>10</sup> A. Wolberg, *J. Mol. Struct.*, 1974, **21**, 61.

The analysis of the spectrum was confirmed by comparison with a  $^{13}\text{C}$  spectrum run at 15.1 MHz,\* wherein the 40% reduction in magnetic field strength allowed identification of the Tl- $^{13}\text{C}$  couplings. We consider the exoplanar position of the metal to be the primary cause for the asymmetry, rather than the position of the ligand X, since changing the ligand from OH to OAc produces little change in the spectrum. Similar effects have been observed in the  $^1\text{H}$  n.m.r. spectra of thallium(III) porphyrins,<sup>11</sup> and hindered rotation of the phenyl rings has been demonstrated<sup>12</sup> by the reversible coalescence of the non-equivalent *ortho*-proton n.m.r. signals of  $\text{Tl}^{\text{III}}\text{TPP}(\text{OAc})$ . An intriguing alternative explanation which finds analogy in recent work<sup>12b</sup> is non-equivalence of the *o*-phenyl protons and carbons due to slow 'inversion' of the thallium atom. The exoplanar position of the metal atom has been confirmed by X-ray crystallographic studies<sup>13</sup> on thallium(III) octaethylporphyrin chloride.

No splitting of the *meta*-carbon signals was observed for  $\text{Tl}^{\text{III}}\text{TPP}(\text{OH})$  (or the acetate), but the resonance

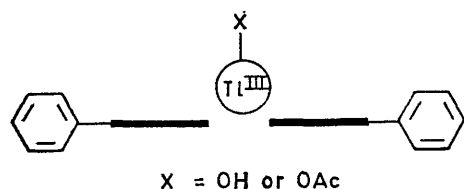


FIGURE 4

was significantly broader than other lines in the spectrum, owing to a small thallium coupling and/or a chemical shift difference.

The  $^{13}\text{C}$  spectrum of  $\text{Tl}^{\text{III}}\text{TOP}(\text{OH})$  displayed just one set of resonances and was assigned by analogy with TPP and its thallium chelate and by comparison with the assignments for TOP. Although significantly broadened, the methyl resonance at 21.0 p.p.m. was not split.

Thallium(III) porphyrins with acetate or cyano ligands did not show resonances in their  $^{13}\text{C}$  spectra due to the carbons in the ligands. This is probably due to intermolecular exchange of the ligand which, at the temperature of determination (*ca.* 35°), could occur at a rate comparable with the expected Tl- $^{13}\text{C}$  couplings, thus broadening the signals beyond detection. Similarly, the methyl proton resonances of the ligand in  $\text{Tl}^{\text{III}}\text{TPP}(\text{OAc})$  in  $\text{CD}_2\text{Cl}_2$  solution occur as a single sharp line at *ca.* 30° which is considerably broadened at lower temperatures (*ca.* -40°).† It is relevant that the  $^{13}\text{C}$  spectrum of thallium(III) acetate in  $[\text{D}_6]\text{dimethyl}$

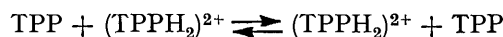
\* We are indebted to Professor J. D. Roberts (California Institute of Technology) for measurement of this spectrum.

† Such a collapse of coupling constant is diagnostic of intermolecular exchange. In addition, the proton resonance of  $\text{Tl}^{\text{III}}(\text{OAc})_3$  (0.07M in  $\text{CD}_3\text{OD}$ ), a single line at 30°, shows coalescence at *ca.* -69° (100 MHz) with resolution of the Tl- $^1\text{H}$  coupling (*ca.* 25.5 Hz) at lower temperatures.

‡ This observation has been the subject of a preliminary publication.<sup>4</sup> A similar effect has been observed by  $^1\text{H}$  n.m.r. in the protonation of *N*-methylporphyrins.<sup>14</sup>

sulphoxide solution displays severely broadened resonances ( $\Delta\nu_{\frac{1}{2}}$  *ca.* 20 Hz) at  $\delta$  20.4 and 175.3 p.p.m., without resolution of the expected Tl- $^{13}\text{C}$  coupling.

The  $^{13}\text{C}$  chemical shifts and assignments for the dications  $(\text{TPPH}_2)^{2+}$  and  $(\text{TOPH}_2)^{2+}$  in  $\text{CDCl}_3$  and trifluoroacetic acid (TFA) solutions are shown in Table 1. The dications in  $\text{CDCl}_3$  were prepared by addition of 2—2.5 equiv. of TFA to a solution of the porphyrin free base. At molar ratios (TFA : TPP) < 2 : 1, two sets of resonances were observed in  $\text{CDCl}_3$  solution. The new resonances grew with increasing TFA (Figure 7) until at the molar ratio *ca.* 2 : 1 only the new resonances were observed.‡ Such behaviour is characteristic of a slow two-proton exchange between TPP and its dication. From the temperature dependence of the  $^1\text{H}$  n.m.r. spectrum at a molar ratio



(TFA : TPP) of *ca.* 1 : 1, we estimate  $\Delta G_{321}^\ddagger$  *ca.* 16.3 kcal mol<sup>-1</sup> for the process.

The patterns of the  $^{13}\text{C}$  resonances from  $(\text{TPPH}_2)^{2+}$  in  $\text{CDCl}_3$  and TFA are very similar, but the shifts measured from internal  $\text{Me}_4\text{Si}$  in the latter solvent indicate a general downfield shift of 1—3 p.p.m. We ascribe this, in part, to an *upfield* shift of the  $\text{Me}_4\text{Si}$   $^{13}\text{C}$  resonance in TFA. This is clear from comparison of the shifts of other non-polar reference compounds in TFA and in  $\text{CDCl}_3$  (Table 2). Both benzene and cyclohexane show a constant downfield shift of 1.5 p.p.m.

TABLE 2

$^{13}\text{C}$  Chemical shifts <sup>a</sup> of some reference signals

$\text{CHCl}_3$	$\text{C}_6\text{H}_6$	$\text{C}_6\text{H}_{12}$	$(\text{CD}_3)_2\text{CO}$ (external)	Solvent
77.0	127.9	26.9	28.2	$\text{CDCl}_3$
78.0	129.5	28.4	30.6	TFA

<sup>a</sup> In p.p.m. downfield from  $\text{Me}_4\text{Si}$ . Samples in 12 mm tubes carrying concentric 5 mm tube of  $(\text{CD}_3)_2\text{CO}$  for field-frequency lock

with respect to  $\text{Me}_4\text{Si}$ , which is most simply interpreted as being due to a high-field shift of the  $\text{Me}_4\text{Si}$  signal. This is confirmed by the  $[\text{D}_6]\text{acetone}$  external reference. The bulk-susceptibility correction for any solute in TFA ( $\chi_v$  -0.583)<sup>15</sup> compared with  $\text{CDCl}_3$  ( $\chi_v$  -0.729)<sup>16</sup> is *ca.* 0.31 p.p.m., *i.e.* the resonance is shifted 0.3 p.p.m. upfield in TFA compared with  $\text{CDCl}_3$ . This is comparable with the observed shifts of cyclohexane and benzene in TFA with respect to  $\text{CDCl}_3$  from the external

<sup>11</sup> R. J. Abraham and K. M. Smith, *Tetrahedron Letters*, 1971, 3335; R. J. Abraham, G. H. Barnett, and K. M. Smith, *J.C.S. Perkin I*, 1972, 2142.

<sup>12</sup> (a) R. J. Abraham, G. E. Hawkes, and K. M. Smith, unpublished results; see also S. S. Eaton, G. R. Eaton, and R. H. Holm, *J. Organometallic Chem.*, 1972, **39**, 179; (b) G. N. LaMar, *J. Amer. Chem. Soc.*, 1973, **95**, 1662; F. A. Walker and G. N. LaMar, *Ann. New York Acad. Sci.*, 1973, **206**, 328; S. S. Eaton and G. R. Eaton, *J.C.S. Chem. Comm.*, 1974, 576.

<sup>13</sup> D. Cullen, E. F. Meyer, and K. M. Smith, to be published.

<sup>14</sup> A. H. Jackson and G. R. Dearden, *Ann. New York Acad. Sci.*, 1973, **206**, 151.

<sup>15</sup> 'Handbook of Chemistry and Physics,' Chemical Rubber Co., 47th edn., 1966.

<sup>16</sup> R. J. Abraham, D. F. Wileman, and G. R. Bedford, *J.C.S. Perkin II*, 1973, 1027.

reference ( $\Delta\delta$  ca. 1.0 p.p.m.) but much less than that of  $\text{Me}_4\text{Si}$  (2.5 p.p.m.). Large solvent shifts of the C-X carbon atom in alkyl halides in polar solvents have been observed by Doddrell *et al.*,<sup>17</sup> who considered them to be due to a reaction field effect; this is not possible in  $\text{Me}_4\text{Si}$ , which has zero dipole moment and thus zero reaction field.

An alternative explanation is similar to that proposed<sup>18</sup> to explain the upfield shifts of  $^{19}\text{F}$  nuclei in a variety of solutes in polar solvents in which the polarisability of the geminal atom (F-C-X) was the dominant factor. It was suggested that non-zero averaging of the solvent electric fields was occurring. Whatever the detailed mechanism, it is clear that this upfield shift must be taken into account when considering protonation shifts in TFA, and this has been done in the subsequent examples.

The  $^{13}\text{C}$  assignments for  $(\text{TPPH}_2)^{2+}$  in TFA were made from SFORD spectra and by specific  $^1\text{H}$  decoupling experiments. Comparison of the data for TPP and  $(\text{TPPH}_2)^{2+}$  in  $\text{CDCl}_3$  and TFA shows the chemical shift changes (p.p.m.) upon protonation illustrated in Figure 5, where a positive sign indicates the resonance from the dication at lower field; the upper and lower values are from the dication in  $\text{CDCl}_3$  and TFA, respectively. Such large changes in chemical shift for the phenyl carbons were not observed for the changes  $\text{TPP} \rightarrow \text{MTPP}$  ( $\text{M} = \text{Zn}^{\text{II}}, \text{Cd}^{\text{II}}, \text{Tl}^{\text{III}}, \text{and Hg}^{\text{II}}$ ). In addition, the protonation shifts for the carbons of the macrocycle show a different pattern to that found<sup>3</sup> for the coproporphyrins and octaethylporphyrin wherein downfield

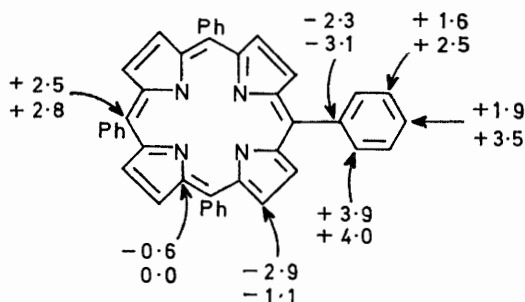


FIGURE 5

protonation shifts occurred at the ' $\beta$ -pyrrole' and *meso*-carbons, with upfield shifts at the ' $\alpha$ -pyrrole' carbons. The protonation-induced  $^{13}\text{C}$  shifts for TPP in  $\text{CDCl}_3$  are therefore probably due to a large change in the mean angle between the macrocycle and the phenyl ring planes<sup>12b,19</sup> with consequent extension of the conjugation in the dication.

The  $^{13}\text{C}$  chemical shifts for the dication  $(\text{TOPH}_2)^{2+}$  in  $\text{CDCl}_3$  are very similar to those for the parent porphyrin, and were assigned directly from this comparison. Protonation-induced shifts were ca. 1 p.p.m. except at

<sup>17</sup> A. Marker, D. Doddrell, and N. V. Riggs, *J.C.S. Chem. Comm.*, 1972, 724.

<sup>18</sup> R. J. Abraham and D. F. Wileman, *J.C.S. Perkin II*, 1973, 1521.

the *meso*- and *ortho*(6'')-positions. This similarity may be due to the *o*-methyl substituent reducing the tendency towards coplanarity of the rings compared with the TPP case. Detailed values are given in Figure 6,

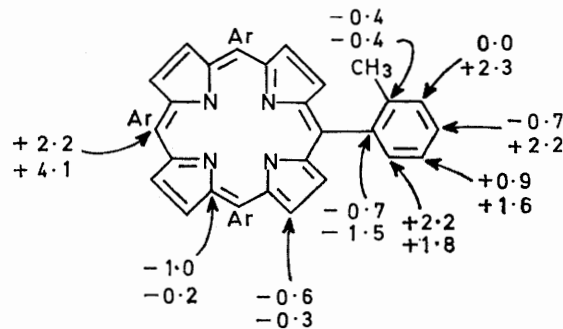


FIGURE 6

where a positive sign indicates the resonance from the dication at lower field; the upper and lower values are from the dication in  $\text{CDCl}_3$  and TFA, respectively.

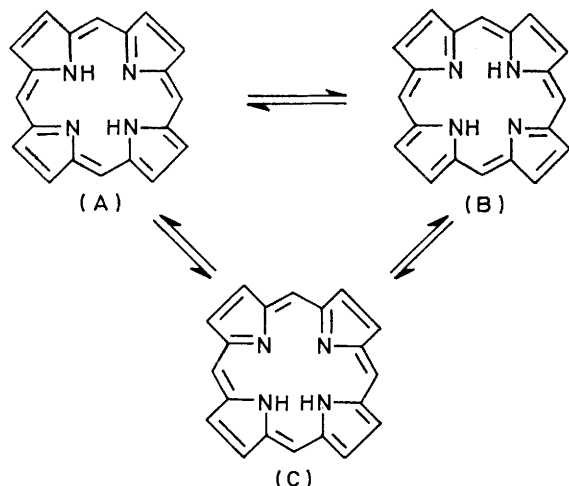
**Thallium couplings.** The  $\text{Tl}$ - $^{13}\text{C}$  couplings found in this study closely follow the trend found<sup>3</sup> for the thallium(III) coproporphyrin chelates, *i.e.* *meso* > ' $\beta$ -pyrrole' > ' $\alpha$ -pyrrole.' The magnitudes of the  $\text{Tl}$ - $^{13}\text{C}$  couplings at the *meso*- and ' $\alpha$ -pyrrole' positions (ca.  $144 \pm 3$  and  $17 \pm 4$  Hz, respectively) are the same for the *meso*-substituted (this study) and peripherally substituted<sup>3</sup> porphyrin chelates. However, the coupling to the ' $\beta$ -pyrrole' positions is markedly greater (ca. 10 Hz) for the *meso*-substituted porphyrins. Probable mechanisms for these couplings have been discussed.<sup>3</sup> It is of interest that of the two *ortho*-methine (C-6'') and two *ortho*-quaternary (C-2'')  $^{13}\text{C}$  resonances for  $\text{Tl}^{\text{III}}\text{TOP}(\text{OH})$ , the lower field doublet of each pair displays the larger  $\text{Tl}$ - $^{13}\text{C}$  coupling; this must reflect stereospecificity ('*cis*' or '*trans*') of both coupling and  $^{13}\text{C}$  chemical shift with respect to the exoplanar metal. In accord with previous studies<sup>11</sup> of  $\text{Tl}$ - $^1\text{H}$  couplings, the axial cyano ligand markedly reduces the  $\text{Tl}$ - $^{13}\text{C}$  couplings compared with hydroxy or acetate.

**NH Tautomerism in porphyrins.** As noted here (Table 1), and previously,<sup>3,4</sup> the  $^{13}\text{C}$  resonances of the ' $\alpha$ -pyrrole' carbons for the porphyrin free bases appear as broad, weak signals in  $\text{CDCl}_3$  solution. Sharp, well defined resonances are obtained for these carbons in metalloporphyrins and porphyrin dications. We have previously concluded,<sup>3</sup> largely on theoretical grounds, that the broadening of the resonances was *not* due to  $^{14}\text{N}$  quadrupole effects, but rather to an intermediate rate of NH tautomerism. Storm *et al.*<sup>20</sup> have shown that this tautomerism may be studied by  $^1\text{H}$  n.m.r. spectroscopy of the ' $\beta$ -pyrrole' protons of TPP and deuteroporphyrin-IX ester (Deutero-IX). They obtained kinetic isotope effects ( $k_{\text{NH}}/k_{\text{ND}}$ ) of 67 for TPP

<sup>19</sup> A. Stone and E. B. Fleischer, *J. Amer. Chem. Soc.*, 1968, **90**, 2735; S. Silvers and A. Tulinsky, *ibid.*, 1967, **89**, 3331.

<sup>20</sup> C. B. Storm and Y. Teklu, *J. Amer. Chem. Soc.*, 1972, **94**, 1745; C. B. Storm, Y. Teklu, and E. A. Sokoloski, *Ann. New York Acad. Sci.*, 1973, **206**, 631.

and 8.9 for Deutero-IX, and rationalised this as inter-conversion of tautomers (A) and (B) by a simultaneous two-proton shift for TPP, but stepwise *via* tautomer (C) for Deutero-IX. Their values for the kinetic isotope effects were obtained by rate measurements at *different* single temperatures for the NH and ND compounds, with consequent neglect of an entropy of activation.



We have measured the rate of tautomerism at three different temperatures for both the NH and ND compounds by observing coalescence in the  $^1\text{H}$  n.m.r. of the '  $\beta$ -pyrrole' protons of TPP and  $NN'$ -dideuterio-TPP ( $[\text{D}_2]\text{TPP}$ ) at 60 and 100 MHz and by a simple line-shape analysis of the  $^{13}\text{C}$  spectra. The rate constants found from the  $^1\text{H}$  n.m.r. coalescence temperatures were used to derive values for the free energy of activation  $\Delta G^\ddagger$  by using Eyring's equation. This gave  $\Delta G^\ddagger_{225}$  *ca.* 11.4 (100 MHz) and  $\Delta G^\ddagger_{213}$  *ca.* 11.0 kcal mol $^{-1}$  (60 MHz) for TPP and  $\Delta G^\ddagger_{265}$  *ca.* 13.5 (100 MHz) and  $\Delta G^\ddagger_{256}$  *ca.* 13.3 kcal mol $^{-1}$  (60 MHz) for  $[\text{D}_2]\text{TPP}$  in  $\text{CDCl}_3$  solution. The  $^{13}\text{C}$  spectrum of  $[\text{D}_2]\text{TPP}$  at  $-60^\circ$  showed separate resonances due to ' $\alpha$ - and  $\beta$ -pyrrole' carbons on 'pyrrole' and 'pyrrolene' rings (Figure 7) thus confirming our suggestion as to the cause of the broadening of the resonances.\* The averaged  $^{13}\text{C}$  resonances observed at  $35^\circ$  showed line-widths for the ' $\alpha$ -pyrrole' carbons of TPP of *ca.* 25 Hz and for the ' $\beta$ -pyrrole' carbons of  $[\text{D}_2]\text{TPP}$  of *ca.* 50 Hz (Table 1). By use of the simple line-shape expression<sup>22</sup> for the fast exchange limit [equation (i)], from these data we estimate the

$$k = \pi/2(\delta_0^4/h^2 + 2\delta_0^2 - h^2)^{1/2} \quad (\text{i})$$

rates of tautomerism ( $k_{\text{NH}}$ ,  $k_{\text{ND}}$ ) at the *same* temperature ( $35^\circ$ ), where  $\delta_0$  (Hz) is the low temperature signal separation and  $h$  (Hz) is the full line-width at half

\* A similar explanation has been proposed for the observation of two broad ' $\alpha$ -pyrrole' carbon resonances in  $^{13}\text{C}$  enriched Copro-III in NaOD solution.<sup>21</sup>

<sup>21</sup> N. A. Matwiyoff and B. F. Burnham, *Ann. New York Acad. Sci.*, 1973, **206**, 365.

<sup>22</sup> A. Allerhand, H. S. Gutowsky, J. Jonas, and R. A. Meinzer, *J. Amer. Chem. Soc.*, 1966, **88**, 3185.

height. This yields the isotope effect ( $k_{\text{NH}}/k_{\text{ND}}$ ) as *ca.* 12. Application of the Eyring relationship gave

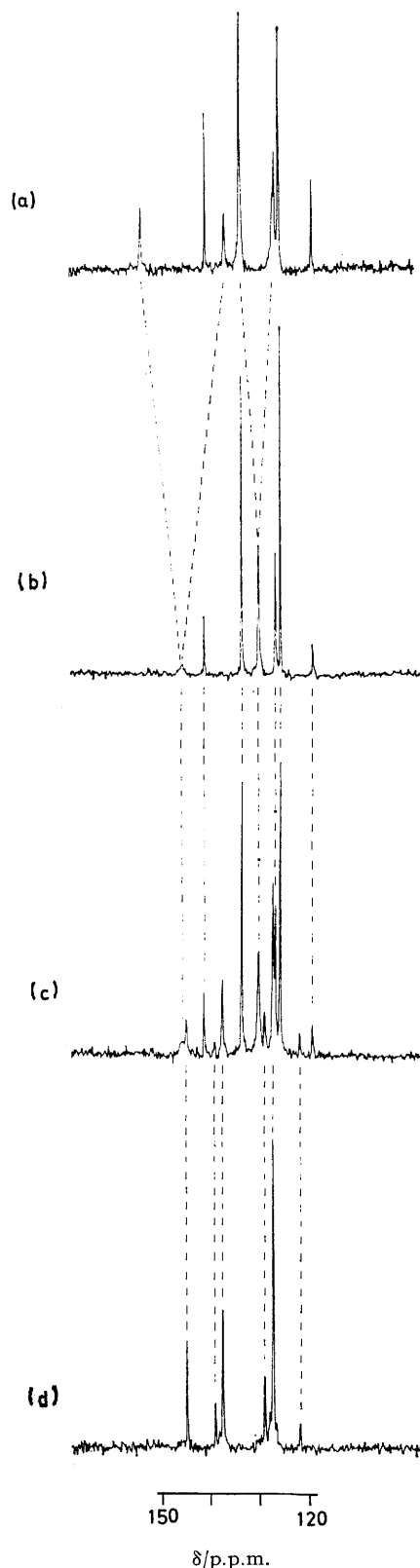


FIGURE 7  $^{13}\text{C}$  Spectra of TPP (0.04M in  $\text{CDCl}_3$ ), (a)  $-60^\circ$ ; (b)  $35^\circ$ ; (c)  $35^\circ$  with 0.05M-TFA; (d)  $35^\circ$  with 0.01M-TFA

$\Delta G_{308}^{\ddagger}$  ca. 12.3 and 13.9 kcal mol<sup>-1</sup> for TPP and [<sup>2</sup>H<sub>2</sub>]-TPP, respectively. From these observations (Figure 8),  $\Delta H_{\text{NH}}^{\ddagger}$  is ca. 9.2,  $\Delta H_{\text{ND}}^{\ddagger}$  ca. 10.8 kcal mol<sup>-1</sup>, and  $\Delta S^{\ddagger}$  ca. -10 ( $\pm 1$ ) cal K<sup>-1</sup> mol<sup>-1</sup> for both protio- and

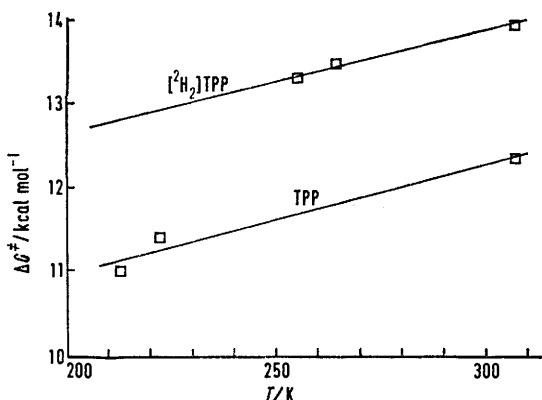
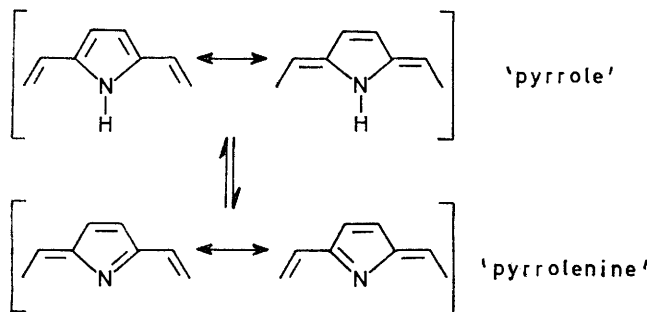


FIGURE 8 Temperature dependence of the activation parameter ( $\Delta G^{\ddagger}$ )

deuterio-compounds. The precise values for the isotope effect and entropy of activation will depend upon the geometry of the transition state for the proton transfer, but the lower magnitude for  $k_{\text{NH}}/k_{\text{ND}}$  found here (*cf.* 67 from Storm *et al.*<sup>20</sup>) does not *a priori* require the mechanism to proceed *via* a simultaneous two-proton shift. The value for the entropy of activation is consistent with that found<sup>23</sup> for sigmatropic [1,5] hydrogen shifts in carbocyclic systems.

The <sup>13</sup>C spectrum of *NN'*-dideuteriocoproporphyrin-I tetramethyl ester ([<sup>2</sup>H<sub>2</sub>]Copro-I) at -75° (CD<sub>2</sub>Cl<sub>2</sub>) also shows the slowing of the tautomerism,<sup>24</sup> demonstrating that this is fundamental to the porphyrin macrocycle and not merely due to the presence of the bulky *meso*-substituents.

Large <sup>13</sup>C chemical shift differences between the 'α-pyrrole' and 'α-pyrroline' resonances (16.9 p.p.m. for TPP; 17.4 and 17.2 p.p.m. for Copro-I) and the 'β' resonances (6.6 p.p.m. for TPP; 5.7 and 5.4 p.p.m. for Copro-I) prompt an assignment. A key difference



between the two situations is that the 'pyrroline' system involves double bonding and conjugation of the

<sup>23</sup> D. S. Glass, R. S. Boikess, and S. Winstein, *Tetrahedron Letters*, 1966, 999.

<sup>24</sup> R. J. Abraham, G. E. Hawkes, and K. M. Smith, unpublished results.

carbons with nitrogen. While suitable models are difficult to envisage, we consider the comparisons<sup>25</sup> shown in Figure 9. The necessary <sup>13</sup>C shifts for pyrazole were estimated from the shifts for 1-methylpyrrole obtained by Rees and Green<sup>25</sup> with the *N*-methyl substituent shifts found by Parker and Roberts<sup>25</sup> in the indole system. This predicts C-3, -4, and -5 of pyrazole to give <sup>13</sup>C resonances at 139.4, 107.2, and 126.4 p.p.m., respectively, which compare favourably with the average C-3 and -5 shift of 134.5 p.p.m. and the C-4 shift of 105.4 p.p.m. found by Weigert and Roberts<sup>25</sup> for pyrazole. Thus, it can be seen that nitrogen (*vs.* carbon) conjugation may shift the α-<sup>13</sup>C resonance downfield by 22–33 p.p.m. and a mean downfield shift of β- and γ-carbons ca. 3.6 p.p.m. On this basis we assign the lower field signal of the α- and

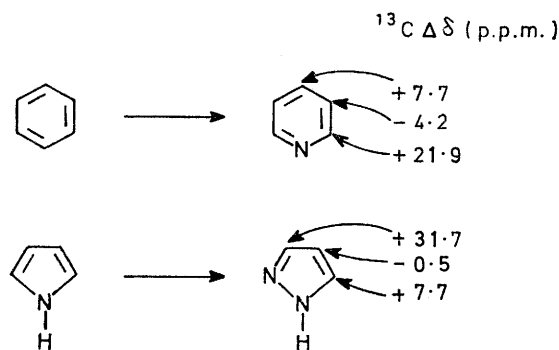


FIGURE 9

β-carbon resonances for TPP and Copro-I to the 'pyrroline' ring.

#### EXPERIMENTAL

The <sup>13</sup>C n.m.r. spectra were obtained with a Varian XL-100 instrument operating in the pulse Fourier transform mode as previously described.<sup>1,3</sup> <sup>1</sup>H N.m.r. spectra were obtained with Varian HA-100 and A-56/60 instruments. Sample temperatures were estimated from the internal chemical shift of methanol (<sup>1</sup>H spectra) and a thermometer inside a spinning sample tube in the probe (<sup>13</sup>C spectra).

The [Hg<sup>II</sup>OAc]<sub>2</sub><sup>26</sup> and other porphyrins were prepared by literature methods, most of which are contained in earlier parts of this Series. Preparations of new compounds are included below.

*meso-Tetra-(o-tolyl)porphyrin.*—Pyrrole (6 ml) and 2-methylbenzaldehyde (10 ml) were added simultaneously to refluxing propionic acid (400 ml) and refluxing was continued for a further 30 min. The mixture was allowed to cool before the product (1.9 g) was filtered off and washed well with methanol. The propionic acid mother liquors were concentrated to ca. 70 ml and set aside over-

<sup>25</sup> P. C. Lauterbur, *J. Chem. Phys.*, 1965, **43**, 360; F. J. Weigert and J. D. Roberts, *J. Amer. Chem. Soc.*, 1968, **90**, 3543; R. G. Rees and M. J. Green, *J. Chem. Soc. (B)*, 1968, 387; R. G. Parker and J. D. Roberts, *J. Org. Chem.*, 1970, **35**, 996; see also J. B. Stothers, 'Carbon-13 NMR Spectroscopy,' Academic Press, London, 1972, ch. 7.

<sup>26</sup> M. F. Hudson and K. M. Smith, *Tetrahedron Letters*, 1974, 2223, 2227.

night. More product was filtered off and washed with methanol; the combined crops were recrystallised from methylene chloride-methanol to give purple plates (3.2 g, 22.0%). Some of this material (1.85 g) was purified by dissolving in methylene chloride (300 ml), adding 2,3-dichloro-5,6-dicyanobenzoquinone (500 mg) in dry benzene (15 ml), and heating under reflux during 6 h. The cooled mixture was stirred with silica gel (35 g) during 15 min and then filtered through a bed of silica gel (30 g). The filtrate was concentrated to *ca.* 80 ml before addition of an equal volume of methanol. The required porphyrin was filtered off to give shining purple plates (1.72 g, 93%), m.p. >300° (Found: C, 85.5; H, 5.6; N, 8.5.  $C_{48}H_{38}N_4$  requires C, 85.9; H, 5.7; N, 8.35%);  $\lambda_{\max.}$  (CHCl<sub>3</sub>) 417.5 ( $\epsilon$  415,400), 482 (2700), 514 (18,800), 546.5 (4800), 581 (5400), and 649.5 nm (2900), *m/e* 670 (100%) and 355 (22);  $\delta$  (CDCl<sub>3</sub>) 8.65 (8H, s,  $\beta$ -H), 7.97 (4H, m, *o*-H), 7.54 (12H, m, *m*-, *p*-H), and 2.05 (12H, m, Ar-CH<sub>3</sub>).

*meso-Tetra-(1-naphthyl)porphyrin.*— 1-Naphthaldehyde (13.6 ml) and pyrrole (7 ml) were added simultaneously to refluxing propionic acid (390 ml), which was refluxed for a further 45 min. After cooling overnight, the porphyrin was filtered off and washed with methanol to give a dark powder (12.5 g). Concentration of the propionic acid mother liquors (to *ca.* 200 ml) afforded a further crop (2 g) of porphyrin (total yield 14.5 g, 71%). This crude material (1.5 g) in boiling chloroform (100 ml) was treated with saturated methanolic zinc(II) acetate (*ca.* 25 ml), refluxed for a further 5 min, and then poured into water. After extraction with a little more chloroform, the dried (Na<sub>2</sub>SO<sub>4</sub>) organic phase was evaporated to give a purple residue which was chromatographed on alumina (Spence type H; 500 g) (elution with chloroform). The red eluates were evaporated to dryness to furnish a purple solid (900 mg, 56%). This was taken up in boiling methylene chloride (200 ml) and treated with a solution of DDQ (300 mg) in dry benzene (10 ml); after refluxing during 5 h, silica gel (t.l.c. grade; 20 g) was added and the suspension was stirred during 15 min. The mixture was filtered through a bed of silica gel (20 g); evaporation of the filtrate gave a purple-red residue which crystallised from methylene chloride-hexane as a purple powder (627 mg, 70%); m.p. >300° (Found: C, 80.6; H, 4.4; N, 6.5; Zn, 6.85.  $C_{60}H_{38}N_4OZn$  requires C, 80.4; H, 4.3; N, 6.25; Zn, 7.3%);  $\lambda_{\max.}$  (CHCl<sub>3</sub>) 423 ( $\epsilon$  599,000), 516 (3500), 548 (23,500), and 584 nm (2000); *m/e* (<sup>64</sup>Zn) 876 (100%), 814 (1), 622 (6), and 438 (15);  $\delta$  (CDCl<sub>3</sub>) 6.9–8.9 (m, Ar-H,  $\beta$ -H). This zinc complex (400 mg) was suspended in chloroform (20 ml) and treated with trifluoroacetic acid (10 ml) and the green solution was stirred for 20 min, then poured into chloroform-water. The solution was neutralised with solid sodium hydrogen carbonate. The organic phase was washed with water, dried (Na<sub>2</sub>SO<sub>4</sub>), and evaporated to dryness to give a purple residue which was chromatographed on alumina (Spence type H; *ca.* 400 g) (elution with methylene chloride). The red eluates were

collected and evaporated to give a purple residue which was crystallised from methylene chloride-n-hexane to give the porphyrin (361 mg, 97%), m.p. >300° (Found: C, 88.2; H, 4.9; N, 6.7.  $C_{60}H_{38}N_4$  requires C, 88.4; H, 4.7; N, 6.9%);  $\lambda_{\max.}$  (CHCl<sub>3</sub>) 422 ( $\epsilon$  391,000), 516 (17,500), 548 (3200), 589 (5800), and 646 nm (1100),  $\lambda_{\max.}$  (CHCl<sub>3</sub> + trace TFA) 454 ( $\epsilon$  111,000), 589 (9000), and 646 nm (21,200);  $\delta$  (CDCl<sub>3</sub>) 6.8–8.8 (m, Ar-H,  $\beta$ -H) and –2.2br (2H, NH); *m/e* 814 (100%), 687 (3), and 407 (18), *m\** 579.8 (814 → 687).

*Aquo-meso-tetra-(o-tolyl)porphyrinatothallium(III) Hydroxide.*—*meso-Tetra-(o-tolyl)porphyrin* (150 mg) in refluxing chloroform (120 ml) was treated with thallium(III) acetate (256 mg, 3 equiv.) in dry methanol (5 ml). After refluxing for a further 1 h the mixture was poured into water. The organic phase was washed with water, dried (Na<sub>2</sub>SO<sub>4</sub>), and evaporated to dryness, and the purple residue was chromatographed on alumina (Merck grade III; *ca.* 100 g) (elution with methylene chloride containing 1% methanol). The red eluates were evaporated to dryness and the residue was crystallised from methylene chloride-n-hexane to give the product (194 mg, 96%) as feathery needles, m.p. >300° (Found: C, 63.7; H, 4.4; N, 5.9.  $C_{48}H_{38}N_4O_2Tl$  requires C, 63.5; H, 4.5; N, 6.2%);  $\lambda_{\max.}$  (CHCl<sub>3</sub>) 433 ( $\epsilon$  506,000), 527 (3100), 566 (20,000), and 604 nm (6500); *m/e* 670 (100%) and 335 (21);  $\delta$  (CDCl<sub>3</sub>) 8.85 (8H, d,  $J_{Tl,H}$  63 Hz,  $\beta$ -H), 8.19 and 7.93 (each 2H, m, *o*-H), 7.59 (12H, m, *m*-, *p*-H), and 2.14 and 1.84 (each 6H, m, 2 × Me). The i.r. spectrum showed no C=O band.

*meso-Tetraphenylporphyrinatothallium(III) Cyanide.*—Chlorin-free *meso-tetraphenylporphyrin* (100 mg) in boiling chloroform (100 ml) was treated with thallium(III) acetate (135 mg, 2.2 equiv.) in dry methanol (5 ml) and heating was continued for a further 15 min. After cooling, silica gel (3 g; t.l.c. grade) was added and the suspension was stirred for 10 min before filtration through a bed of silica gel. Evaporation of the filtrate left a purple residue which was dissolved in chloroform (60 ml), treated with a solution of sodium cyanide (410 mg) in dry methanol (10 ml), and then stirred in the dark during 3 days. Silica gel (3 g; t.l.c. grade) was added and the suspension was stirred for 10 min before filtration through a bed of silica gel. The filtrate was evaporated and the residue was crystallised from chloroform-methanol to give the product (130 mg, 95%), m.p. >300° (Found: C, 63.3; H, 3.7; N, 8.2.  $C_{46}H_{32}N_5OTl$  requires C, 63.2; H, 3.7; N, 8.0%);  $\lambda_{\max.}$  433 ( $\epsilon$  647,600), 531 (3400), 570 (21,500), and 611 nm (12,800), *m/e* 843 (7%), 614 (100), and 307 (55);  $\delta$  (CDCl<sub>3</sub>) 9.01 (8H, d,  $J_{Tl,H}$  59 Hz,  $\beta$ -H), 8.37 and 8.07 (each 4H, m, *o*-H), and 7.74 (12H, m, *m*-, *p*-H).

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[4/1753 Received, 20th August, 1974]