The Crystal Structure and Molecular Stereochemistry of $\alpha,\beta,\gamma,\delta$-Tetra(4-pyridyl)porphinatomonopyridinezinc(II). An Appraisal of Bond Strain in the Porphine Skeleton[1]

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Abstract: Crystals of $\alpha,\beta,\gamma,\delta$-tetra(4-pyridyl)porphinatomonopyridinezinc(II) utilize the space group C2/c and a four-molecule unit cell with a = 14.748, b = 18.136, c = 13.622 Å, and β = 100.66°. Some 6434 counter-measured intensity data retained as observed from θ–2θ scans extending to $(\sin\theta)/\lambda = 0.82$ Å^{-1} led to a Fourier synthesis requiring trivial corrections for nonconvergence. The superior internal consistency of the atomic positions from this synthesis was nearly matched in the set of corresponding *averaged* positions from three least-squares refinements that (1) ignored hydrogen atoms, (2) included hydrogen contributions, and (3) excluded chromium sphere data (<20% of the whole) with *pro forma* retention of hydrogen contributions. The radius of the central core (Ct–N) of the porphine skeleton is 2.047 (2) Å, smaller than the Zn–N bond length (2.073 Å) because the zinc atom lies 0.33 Å out-of-plane toward the pyridine ligand; the axial Zn–N distance is 2.143 Å. Comparison with a nickel deuteroporphyrin shows that the increase in the Ct–N radius from 1.960 (4) to 2.047 (2) Å in the respective nickel and zinc porphyrins is accompanied by significant alterations in the averaged lengths of two classes of bonds in the porphine skeleton: an increase of 0.031 (4) Å for the bonds joining methine to pyrrole carbon atoms and a smaller decrease of 0.014 (4) Å for the N–C bonds. Strain is minimized for a Ct–N radius of ~2.01 Å, and the resistance of the porphine skeleton to undue contraction or expansion constitutes a fundamental constraint on the coordination group. Out-of-plane displacement with the secure attachment of a single axial ligand is preferred by an overlarge cation of modest complexing power such as Mg^{2+} or Zn^{2+}.

Accurate determination of the molecular stereochemistry of the monopyridinezinc(II) derivative of $\alpha,\beta,\gamma,\delta$-tetra(4-pyridyl)porphine (hereinafter designated as PyZnTPyP; see Figure 1 for a skeletal diagram) was undertaken with the following considerations in view.

By reason of its structure and charge distribution, the porphinate anion forms chelates with cations of notably varied size and electronic structure, but with the imposition of severe constraints on the configurational geometry and the bond parameters of the coordination groups.[3,4] It follows, of course, that the porphine skeleton is itself subjected to varying radial strain in its mean plane when cations of very different ionic (or covalent) radius are complexed. Such strain is evident in the skeletal bond angles,[4] but is not so readily detected in the bond lengths; the study reported herein demonstrates that two classes of bonds in the porphine skeleton do undergo quite significant alterations in length when the cations are as different in size and bonding characteristics as the zinc and nickel ions. A most useful parameter for discussion of this general subject is the radius of the central core of the porphine skeleton (Ct–N), the distance (averaged when necessary) from the center to the porphine nitrogen atoms; this radius coincides with the complexing bond length only when the cation is centered in the mean plane.

Noting that the d^{10} Zn^{2+} and the d^0 Mg^{2+} have nearly the same effective size for the same coordination number, a study of the similarities and the differences in composition, stereochemistry, and bonding in the metalloporphyrins formed by these ions is of interest in its own right, and may shed some light on the preference exhibited by the chlorophylls for the magnesium ion. Octahedral coordination of monodentate neon-shell ligands is generally observed with Mg^{2+}, less characteristically so with Zn^{2+}; when not unduly constrained by the stoichiometry, the zinc ion usually prefers to make fullest use of its more tightly bound set of sp^3 valence-shell orbitals for covalent bonding in tetrahedral coordination. It is clear, however, that the configuration of the complexing bonds to the four porphine nitrogen atoms can be only slightly ruffled and/or domed; that, indeed, it must remain at least quasiplanar.[3,4] Thus, a four-coordinate zinc porphyrin wherein both the $4p_z$ and the higher lying $4d_{z^2}$ orbitals of the central atom are effectively excluded from the bonding should readily add either one or two axial ligands to put the Zn(II) atom into square-pyramidal or octahedral coordination, respectively. Spectrophotometric studies by Miller and Dorough[5] of the addition in benzene solutions of pyridine to the Zn(II) and Mg(II) derivatives of $\alpha,\beta,\gamma,\delta$-tetraphenylporphine and $\alpha,\beta,\gamma,\delta$-tetraphenylchlorin (to be written as MTPP and MTPC with M = Zn or Mg) are quite suggestive in this connection.

For the complexing of a single molecule of pyridine to the Zn(II) atom of ZnTPP or ZnTPC, Miller and Dorough obtained equilibrium constants and $-\Delta H°$ values at 29.9° of 3720 ± 270 and 9200 cal/mol for the porphyrin, 5270 ± 300 and 9000 cal/mol for the chlorin; but within the temperature range covered, 20.3–39.8°, they could find no evidence for the complexing of a second molecule of pyridine. Equilibrium constants obtained at 29.9° for the second stage of complexing pyridine by the respective monopyridinemagnesium(II)

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[3] T. A. Hamor, W. S. Caughey, and J. L. Hoard, *J. Amer. Chem. Soc.*, 87, 2305 (1965).

[4] J. L. Hoard in "Structural Chemistry and Molecular Biology," A. Rich and N. Davidson, Ed., W. H. Freeman and Company, San Francisco, Calif., 1968, pp 573–594.

[5] J. R. Miller and G. R. Dorough, *J. Amer. Chem. Soc.*, **74**, 3977 (1952).

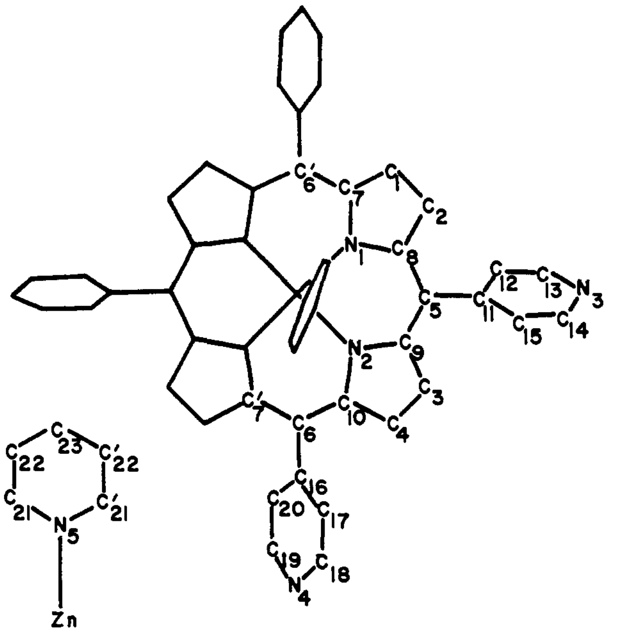

Figure 1. The skeletal framework of the PyZnTPyP molecule as adapted from a computer-drawn diagram; the slight ruffling of the porphine skeleton, unseen here, is indicated in Figure 2. Primed and unprimed symbols carrying the same subscripts identify pairs of atoms related by the twofold axis on which are centered the zinc atom and the N_5 and C_{23} atoms of the complexed pyridine molecule (see inset). The numbering scheme shown for atoms in the asymmetric unit of structure is maintained in Tables I–V.

species, PyMgTPP and PyMgTPC, were 0.577 ± 0.03 and 0.833 ± 0.047, and were accompanied by correspondingly small values of $-\Delta H°$, about 2600 cal/mol for both the porphyrin and the chlorin. Equilibrium constants at 29.9° for the first stage of complexing pyridine to MgTPP and MgTPC were estimated as 2000 and 4000, respectively, both smaller than the corresponding values for the formation of PyZnTPP and PyZnTPC.

Earlier studies of porphyrin structure[4,6,7] suggest that the failure of the Zn(II) atom to add a second axial ligand is not the expression of a general preference for five over six coordination, but is a specific consequence of stereochemical constraints imposed by the porphine skeleton. The longest of the M–N bonds reported for metalloporphyrins in which the metal atom is centered among the four porphine–nitrogen atoms, 2.01 Å, involves the strongly complexing palladium(II) atom in characteristic square-planar coordination,[8] and it may be doubted whether a similarly exact centering of the less strongly complexing Zn(II) atom at a Zn–N distance[7] $\gtrsim$2.05 Å corresponds to the most stable four-coordinate geometry. Structure determination for a zinc porphyrin lacking axial ligands would provide a most stringent test of whether, independent of coordination number, the Zn(II) atom generally takes an out-of-plane position from the porphine nitrogen atoms. The crystalline zinc porphyrin supplied by Professor A. E. Martell for the study reported herein was initially supposed to have no axial ligands, but the presence of complexed pyridine became evident at an early stage of the structure analysis. It will be seen, however, that the quantitative stereochemical parameters of the coordination group in the PyZnTPyP molecule together with analogous data from a six-coordinate magnesium porphyrin provide the structural basis for understanding the differing thermodynamic stabilities of the several pyridine complexes.[5]

Determination of Structure. The high quality of the lustrous purple crystals of PyZnTPyP was immediately apparent in the virtually complete absence of streaking and spot diffuseness on oscillation and Weissenberg photographs taken during the preliminary X-ray studies. Indeed, the single crystal employed for the quantitative measurement of diffracted intensities on a Picker four-circle diffractometer gave extraordinarily low background counts (for which the clean mounting was in part responsible) while displaying no evidence whatever of deterioration during some 11,500 θ–2θ scannings of peak positions. The observed X-ray symmetry of 2/m, the pattern of systematic extinctions, and the negative results of sensitive tests for piezoelectricity (using a Geibe-Schiebe detector) led initially to the choice of C2/c as the probable space group;[9] this choice was supported in every detail by the subsequent analysis of structure. Concordant values of the lattice constants were obtained from two sets of measurements carried out on different diffractometers with significant variations in technique. The first measurements utilized only low-order reflections for which the Mo Kα doublet ($\bar{\lambda}$ 0.71069 Å) was unresolved; the more precise later set utilized the well-resolved Mo Kα_1 (λ 0.70926 Å) components of 24 reflections, distributed equally between plus and minus values of 2θ, all with $|2\theta| \gtrsim$ 34°. Angular settings in this latter case were obtained from the automatic centering program supplied with the computer-controlled diffractometer, each setting being repeated until a stable average resulted; the precision of the settings was confirmed manually for four reflections chosen at random. All measurements were made at the ambient laboratory temperature of 20 ± 1°. Least-squares refinement[10] of the diffraction geometry of these 24 reflections led to the lattice constants, a = 14.748 (2), b = 18.136 (3), c = 13.622 (2), cos β = −0.18499 (7) or β = 100.66°. For a cell content of four PyZnTPyP molecules the density was calculated to be 1.413 g/cc; the experimental density, as measured by flotation, was found to be 1.405 g/cc, with 0.002 g/cc as the root-mean-square deviation calculated from three independent determinations.

Diffracted intensities were measured with Zr-filtered Mo Kα radiation at a take-off angle of ~2° on a computer-controlled four-circle diffractometer; the specimen crystal, 0.25 × 0.20 × 0.08 mm, was mounted with its shortest dimension nearly parallel to the axis of the goniometer head. Each θ–2θ scan, taken at the leisurely rate of 0.5°/min, included a variable increment in angle above the minimum (1° at 2θ = 0) to allow for spectral dispersion; background counts each of 40 sec duration were taken at the extremes of the scan. All independent reflections, ~8200, for which $(\sin \theta)/\lambda \lesssim 0.818$ Å^{-1}, were thus scanned. The intensities of

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(6) J. L. Hoard, G. H. Cohen, and M. D. Glick, *J. Amer. Chem. Soc.* **89**, 1992 (1967).

(7) M. D. Glick, G. H. Cohen, and J. L. Hoard, *ibid.*, **89**, 1996 (1967).

(8) E. B. Fleischer, C. K. Miller, and L. E. Webb, *ibid.*, **86**, 2342 (1964).

(9) "International Tables for X-Ray Crystallography, Vol. I. Symmetry Groups," The Kynoch Press, Birmingham, England, 1952, p 101.

(10) Use was made of the Pick II computer program, a revision in this laboratory of W. C. Hamilton's Mode I program.

three standard reflections, periodically measured, displayed no trend with time during the course of the measurements; they did vary as a group, up and down, during a 24-hour period by as much as 2% from the mean, apparently reflecting the imperfect stabilization of the power supply. Following recording of the inner 4200 reflections the centering and alignment of the crystal was found, by direct rechecking, to be as nearly perfect as at the outset of the measurements. Indeed, the exceptionally low background together with the slow rate of scan allowed quite weak reflections at modest and higher values of 2θ to be clearly delineated on the logarithmic scale of the recorder chart as resolved doublets accurately positioned within the scanning range. With the cited dimensions and mounting of the PyZnTPyP crystal, a linear absorption coefficient for Mo Kα radiation of only 0.76 mm^{-1}, and the technique employed for intensity measurement, the errors resulting from the neglect of absorption corrections in the intensity data were seen to be of comparable magnitude with those produced by the externally produced variations in the intensity of the incident X-ray beam. The net intensities, consequently, were reduced to a set of relative squared amplitudes, $|F_o|^2$, without correction for absorption, by application of the standard Lorentz and polarization factor (Lp).

Retention as objectively observed of those data for which $|F_o| > 0.675\sigma_F$, σ_F being the standard deviation computed from $\sigma_F{}^2 = (Ct + k^2B)/4|F_o|^2(Lp)^2$, Ct the total count from the scan, k the ratio of scanning time to total background counting time, and B the total background count, left 6434 independent data for the determination and least-squares refinement of structure. Only reflections that could be seen as well-resolved peaks on the recorder chart were thereby retained.

A three-dimensional Patterson synthesis of the $|F_o|^2$ data lying within the Cu Kα limiting sphere led at once to placement of the zinc atoms on twofold axes in the special positions 4 (e):[9] $0, y, {}^1/_4;\ 0, \bar{y}, {}^3/_4;\ {}^1/_2, {}^1/_2 + y, {}^1/_4;\ {}^1/_2, {}^1/_2 - y, {}^3/_4$ of C2/c. The positions of all other atoms were then developed from Fourier and difference syntheses with initial phasing based on the contributions of the zinc atoms to the structure amplitudes. Initial refinement of the coordinates and isotropic thermal parameters of the 29 atoms (excluding hydrogen) in the asymmetric unit (half of the molecule of required C_2 symmetry) utilized full-matrix least-squares minimization of the function,[11] $\Sigma w(|F_o| - k|F_c|)^2$. Three distinctive variants of anisotropic refinement that utilized all of the 6434 data in block-diagonal[12] least-squares minimization of the foregoing function were then carried independently to convergence. Empirical weights ($w = 1/\sigma^2$) were calculated from

$$\sigma = \sum_0^3 a_n |F_o|^n$$

the a_n being coefficients from the least-squares fitting of the curve

$$||F_o| - |F_c|| = \sum_0^3 a_n |F_o|^n$$

The values of $|F_c|$ in each refinement came from a sensibly final description of the structure.

Refinement I in this series did not include the hydrogen atoms; it was followed by a Fourier difference synthesis whereby all of these atoms were placed in apparent positions ~0.95–1.00 Å from the carbon atoms to which they were attached. Refinement II did include the hydrogen atoms, initially in fixed positions with thermal parameters taken from those of the associated carbon atoms; subsequent relaxation of these restrictions allowed three of the 15 apparent C–H distances in peripheral bonds to be ridiculously altered by >0.15 Å. (The nature of the final refinement III is specified below.)

It was then noted that the introduction of the hydrogen contributions in II had given, as compared with I, systematic shifts in the apparent positions of the 15 hydrided (hydrogen carrying) carbon atoms in the asymmetric unit while leaving the positions of the remaining 14 atoms virtually unaltered. Inasmuch as both I and II were dominated by the numerous higher resolution amplitudes that, in turn, were dominated by the scattering from the inner shells of the carbon and other heavier atoms, the shifts in the positions of the hydrided carbon atoms were necessarily so small as to carry individually no more than doubtful significance; they were, nonetheless, systematically cumulative in their overall effect, which was to give objectively significant shrinkings of the aromatic ring skeletons containing the hydrided carbon atoms. The objective significance of this shrinkage was revealed in the differing values obtained for the averaged length of the ten structurally nonequivalent C–C bonds in the 4-pyridyl and pyridine skeletons: 1.390 Å from I and 1.379 Å from II, each carrying a formally calculated value of ~0.0015 Å for the weighted standard deviation of the mean.[13]

The positions of the effective centroids of electron density (the "atomic positions") that are given by least-squares refinement are dependent upon (1) the scope of the data, (2) the precision of intensity measurement, and

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[11] These computations followed W. R. Busing, K. O. Martin, and H. A. Levy, "OR-FLS, A Fortran Crystallographic Least-Squares Program," ORNL-TM-305, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1962. Atomic form factors, from D. T. Cromer and J. L. Mann (*Acta Crystallogr.*, **A24**, 321 (1968)), with corrections, real and imaginary, for the anomalous scattering of the zinc atom from D. T. Cromer, *ibid.*, 18, 17 (1965), were used in least-squares refinements of the structural parameters.

[12] One complete cycle of the standard Busing–Martin–Levy full-matrix anisotropic refinement[11] of the PyZnTPyP structural parameters on the IBM 360/65 computer must be approximated by a three-stage sequential refinement by parts (at nearly prohibitive cost). Our block-diagonal program REFINE, written by J. J. Park, has consistently given results that differ insignificantly from those given by the standard full-matrix refinement when applied to data sets in which the data–parameter ratio ranged upward from eight and the refinement was dominated by the higher resolution Fourier coefficients from beyond the Cr Kα sphere. In the study now reported the data–parameter ratio was 26.8, and 80.5% of the amplitudes were from beyond the Cr Kα limit. When, indeed, the results of the block-diagonal refinement II were fed into the three-stage full-matrix operation, the most striking change was an alteration of 0.003 Å in one C–C bond length lying within a 4-pyridyl substituent; but the averaged change in these peripheral C–C distances was less than 0.001 Å.

[13] We have obtained quite analogous results for tropolonato complexes. Thus, for a triclinic crystal of a tetrakis(tropolonato)thorium(IV) complex,[14] the alternative least-squares refinements of structure that (I) excluded or (II) included the hydrogen contributions gave 1.396 (3) or 1.384 (3) Å, respectively, for the averaged lengths of the 16 symmetry-independent bonds between pairs of hydrided carbon atoms in the four tropolonato ligands. The refinement utilized 6792 independent amplitudes with $0 < (\sin\theta)/\lambda < 0.69$ Å^{-1}, giving a data–parameter ratio of 17.8. One judges that the internuclear C–C distance in the tropolonato ring is not likely to be smaller than the standard 1.395 (3) Å in benzene.

[14] V. W. Day and J. L. Hoard, *J. Amer. Chem. Soc.*, **92**, 3626 (1970).

(3) the degree of elaboration of the theoretical model employed to calculate amplitudes. In many current reports of structure determinations, moderate emphasis is put on (2) and still greater emphasis on (3), both, however, at the expense of (1); studies utilizing only data from within the chromium Kα limiting sphere fall automatically into this category. In our analysis of the PyZnTPyP structure, we have exercised unusual care in the measurement of intensities and, still more important, we have extended the scope of the measurements to the highest practicable scattering angles on the fundamental premise that a physically definitive determination of structure should display the minimum rather than the maximum dependence on uncertain or unnecessary elaborations of the theoretical model. Our data–parameter ratio (hydrogen parameters not counted) was 26.8 and, of the 6434 amplitudes used in the refinements, some 39 and 80% were from beyond the respective copper Kα and chromium Kα limits. Consequently, the exponentially varying thermal parameters of all atoms (except hydrogen) were thereby restricted, in unwonted fashion, to certainly narrow and, quite possibly, realistic ranges of reasonable variation. Shifts in the apparent positions of the carbon and all heavier atoms resulting from the most significant change in the theoretical model[15]—the introduction of the hydrogen contributions—were devoid of significance excepting those nearly trivial, but uniformly cooperative, shifts detailed above for the hydrogen-carrying carbon atoms. But inasmuch as we wished to derive from the X-ray data effective centroids of electron density for the 15 hydrided carbon atoms that would best approximate to the nuclear positions, there remained the question of which refinement, I or II, was better suited to this end.

That the refinement II gave an aromatic C–C bond length significantly farther below the standard 1.395 (3) Å internuclear value than did I could be discounted on the presumption that an averaged foreshortening of ~0.016 Å in the derived length was not too large to be attributable to the complex motions of the peripheral groups. It could further be argued that inclusion of the hydrogen contributions recognized the asphericity for X-ray scattering of the carbon atoms (albeit only that associated with the C–H bonds), and that it certainly led to a slightly lower value of the conventional $R = \Sigma||F_o| - |F_c||/\Sigma|F_o|$.[16] But it also could be argued that the principal role played by the hydrogen contributions was to supply the purely mathematical process of overall least-squares minimization with additional parameters of all too easy virtue, and thus give a lower R at the expense of physical reality.[17] In consideration of these points, we were led to a final least-squares refinement III and, subsequently, to a detailed appraisal of the nearly convergent Fourier synthesis.

Refinement III, with a data–parameter ratio of 20.8, utilized the ~5200 higher resolution amplitudes lying wholly outside the chromium Kα limiting sphere; hydrogen atoms, assigned fixed positions and thermal parameters at the values obtained from II, were included, but on an essentially *pro forma* basis since the contribution of these atoms was nontrivial only for the excluded chromium sphere data. This refinement, indeed, was designed to give effective centroids of electron density for the inner shells of the carbon and other heavier atoms and thus approximate closely to the nuclear positions. Apart from the 15 hydrided carbon atoms, the description of the PyZnTPyP framework differed immaterially from that given by the earlier refinements; for the hybrided carbon atoms, however, the positions from III were uniformly closer to those from I than from II. Thus the averaged length of the ten structurally nonequivalent C–C bonds in the 4-pyridyl and pyridine skeletons from III was 1.389 Å, with a weighted esd of 0.002 Å, as compared with 1.390 and 1.379 Å, respectively, from I and II. Furthermore, the values for the averaged length of the two structurally nonequivalent C_b–C_b bonds in the pyrrole rings from I, II, and III were 1.359, 1.350, and 1.356 Å, respectively, with weighted esd values in the 0.003–0.004 Å range. For all twelve structurally nonequivalent bonds between pairs of hydrided carbon atoms, the averaged difference in length given by I and II was 0.011 Å, by I and III a trivial 0.001 Å.

The theoretically most fundamental centroids of electron density for the hydrided carbon and the nitrogen atoms were then obtained by the objective evaluation, following Shoemaker, *et al.*,[18] of the peak positions in the Fourier synthesis of the 6434 independent F_o coefficients. Using the accurately known coordinates of the zinc atom, the observed amplitudes were first corrected for that small part of the zinc contributions attributable to anomalous dispersion so as to obtain the theoretically soundest representation of the real electron density. Only the rather special (040) amplitude was in evident need of correction for extinction. Corrections for nonconvergence of the Fourier series, estimated in the standard fashion as the departures from exact reproducibility of the preassigned peak positions in the corresponding Fourier synthesis of the calculated amplitudes, were almost negligible, *e.g.*, no correction to a C–C or C–N bond length exceeded 0.002 Å and the average correction was less than 0.001 Å.

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[15] During the course of this extended study it was further ascertained that the effect on the apparent atomic positions of neglecting the anomalous dispersion corrections, real and imaginary, to the form factor of the zinc atom was even more tenuous than that of including the hydrogen contributions. It follows that modest deficiencies in the atomic form factors, as these latter are calculated using approximate wave functions, are rather unimportant in a structure determination based upon data of sufficiently wide scope. Full copper sphere data probably suffice, chromium sphere data certainly not.

[16] The "high" R values of 0.09–0.10 from the refinements simply reflected the stringency of the tests applied to the comparisons of calculated and observed amplitudes. Although we were careful to include only reflections that were certainly observed (*vide supra*), we were equally careful to set the rejection criterion low enough ($|F_o| < 0.675\sigma_F$) to retain numerous weak reflections registered predominantly in the higher range of $(\sin\theta)/\lambda$. The average value of $||F_o| - |F_c||$ for such reflections was not significantly different from that for the less structure-sensitive data. The lowered percentage accuracy of intensity measurement for the weak structure-sensitive reflections, though regrettable, was unavoidable; but it had no bearing upon the obligation of the structural model to account, as best it could, for the physical reality of these reflections.

[17] The two-center partial superposition of spherical electron densities as a model for the X-ray scattering from a pair of bonded atoms becomes grossly approximate when one of the atoms is hydrogen. The mathematical pliability of such a model, one atom being hydrogen, as a minor component during overall least-squares minimization is quite evident.

[18] D. P. Shoemaker, J. Donohue, V. Schomaker, and R. B. Corey, *J. Amer. Chem. Soc.*, 72, 2328 (1950). Objective evaluation of a peak position utilized the least-squares fitting of a gaussian to 27 grid points immediately surrounding the peak. This is a well-tested procedure.[19]

[19] G. L. Glen, J. V. Silverton, and J. L. Hoard, *Inorg. Chem.*, 2, 250 (1963); S. Richards, B. Pedersen, J. V. Silverton, and J. L. Hoard, *ibid.*, 3, 27 (1964).

The Fourier positions or, more properly, the bond lengths calculated therefrom displayed an internal consistency that was quite beyond the reach of any of the least-squares refinements. For each subset of C–C or C–N bonds in which a common length was the stereochemically rational expectation, the mean deviation from the averaged length in the Fourier values was notably smaller than either the mean deviation or the (root-mean-square) estimated standard deviation in the least-squares value from I, II, or III. The averaged values of the sensitive C–C and C–N bond lengths in the 4-pyridyl and pyridine groups given by the Fourier synthesis were in best agreement with those given by III, in poorest agreement with those from II. A still better matching of the least-squares with the Fourier results in respect both to internal consistency and the averaged values of the aromatic bond lengths in peripheral groups was then achieved by using the (equally weighted) averaged positions from all three least-squares refinements; a common value, 1.386–1.387 Å, for the averaged length of the 10 aromatic C–C bonds was thereby obtained.

Thus the Fourier synthesis and the least-squares refinement III reinforce one another in suggesting that refinement II gave undue weight and/or mathematical freedom[17] to the hydrogen contributions in the computationally successful, but physically deceptive, process of improving the apparent agreement overall between calculated and observed amplitudes—so much so, indeed, that the explicit neglect of the hydrogen atoms in I was a preferable alternative.[20] Although the malleability of I and II to the exclusion or inclusion of hydrogen contributions was countenanced only by the low-resolution data (<20% of the total) from within the chromium sphere and, consequently, was largely repressed by the more numerous and much more structure-sensitive data from beyond the Cr Kα limit, only data of sweeping scope and sensitivity could provide the fundamental basis for definitive conclusions. Had only chromium sphere data been available for the PyZnTPyP analysis, we would have been driven to employ the crude rigid-body approximation[21] for the peripheral groups and we would have lost all prospect of attaining the quantitatively definitive description of the porphine skeleton and coordination group that is, in fact, provided by any and all of the refinements described above. Such undue sensitivity to every detailed feature of the model in least-squares refinement is greatly reduced by simply extending the range of measurement to include a full copper sphere of data, two-thirds of which lies beyond the Cr Kα limit. We have demonstrated the validity of this familiar fact specifically for the PyZnTPyP structure in an earlier analysis that utilized an independently measured set of copper sphere data with a data–parameter ratio of 13; indeed, our Discussion of Results, presented below essentially as written on the basis of the earlier study, has merely been reinforced at every point by the exhaustive analysis set forth above.[22]

Table I. Atomic Coordinates in the Unit Cell of the Crystal

Atom type	—Coordinates with standard deviations^a—		
	10^4x	10^4y	10^4z
Zn	0	1449 (0)^b	1/4
N_1	409 (2)	1257 (1)	1151 (2)
N_2	1355 (2)	1277 (1)	3218 (2)
N_3	4666 (2)	1090 (2)	690 (3)
N_4	2489 (2)	1208 (2)	8040 (2)
N_5	0	2631 (2)	1/4
C_1	418 (2)	1303 (2)	−538 (2)
C_2	1307 (2)	1313 (2)	−65 (2)
C_3	2937 (2)	1147 (2)	3523 (2)
C_4	2660 (2)	1147 (2)	4423 (2)
C_5	2110 (2)	1253 (2)	1738 (2)
C_6	1113 (2)	1242 (2)	4963 (2)
C_7	−145 (2)	1261 (2)	229 (2)
C_8	1302 (2)	1277 (2)	993 (2)
C_9	2115 (2)	1233 (2)	2770 (2)
C_{10}	1669 (2)	1234 (2)	4223 (2)
C_{11}	2997 (2)	1206 (2)	1389 (2)
C_{12}	3203 (3)	587 (2)	863 (3)
C_{13}	4040 (3)	557 (3)	533 (4)
C_{14}	4470 (3)	1662 (3)	1189 (4)
C_{15}	3652 (3)	1753 (3)	1550 (4)
C_{16}	1592 (2)	1230 (2)	6029 (2)
C_{17}	2202 (2)	1788 (2)	6428 (3)
C_{18}	2629 (2)	1751 (2)	7422 (3)
C_{19}	1902 (3)	683 (2)	7655 (3)
C_{20}	1446 (2)	662 (2)	6669 (2)
C_{21}	81 (3)	3010 (2)	3352 (2)
C_{22}	93 (3)	3767 (2)	3389 (3)
C_{23}	0	4154 (3)	1/4

^{a} Numbers in parentheses are the estimated standard deviations. ^{b} The unrounded figures are 1449.2 (0.3).

Listed in Table I are the atomic coordinates of the asymmetric unit as the averaged values from the three least-squares refinements;[23] the estimated standard deviations are equally characteristic of refinements I and II. Table II gives the associated anisotropic thermal parameters and Table III is a listing of the "hydrogen positions." Interatomic distances and angles within the molecule are carried in the respective Tables IV and V.[24]

Discussion of Results

The PyZnTPyP molecule, with the atoms numbered in agreement with Tables I–V, is illustrated in the perspective drawing of Figure 1. The twofold axis required of the molecule in the crystal passes through the zinc atom and the 1 and 4 positions (atoms N_5 and C_{23}

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(20) This conclusion in no way involves the observation that refinement I gave the aromatic C–C distance that was least depressed from the standard internuclear value. (Clearly the explicit neglect of the C–H bond density in the model offset in part the effects of group thermal motions in foreshortening the derived bond lengths.)

(21) *Cf.* S. LaPlaca and J. A. Ibers, *J. Amer. Chem. Soc.*, **87**, 2581 (1965).

(22) Notification of acceptance for publication (Feb 1969) of the original paper was accompanied by a referee's critical remarks that seemingly drew upon an extensive experience with chromium sphere data. Doubting that endless elaboration of an approximate model in least-squares refinement is a fundamentally objective substitute for data of definitive range in the search for physically realistic atomic positions, we were led into the costly study detailed herein as the one fully convincing means of establishing the facts. We note that the earlier analysis (hydrogen atoms ignored) gave an averaged length for the ten aromatic C–C bonds of 1.396 Å, with a mean deviation of 0.008 Å as compared with a (root-mean-square) esd of 0.010 Å; *cf.* ref 20.

(23) A table of observed and calculated structure amplitudes from this analysis has been deposited as Document No. NAPS-00812 with the ASIS National Auxiliary Publication Service, c/o CCM Information Corp., 909 3rd Ave., New York, N. Y. 10002. A copy may be secured by citing the document number and by remitting $3.00 for photoprints or $1.00 for microfiche. Advance payment is required. Make checks or money order payable to ASIS–NAPS.

(24) Estimated standard deviations in these bond lengths and angles were calculated following W. R. Busing, K. O. Martin, and H. A. Levy, "OR-FFE, A Fortran Crystallographic Function and Error Program," ORNL-TM-306, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1964.

Table II. Thermal Parameters of the Atoms in the Crystal

Atom type	Anisotropic parameters (Å²) with standard deviations[a] B_{11}	B_{22}	B_{33}	B_{12}	B_{13}	B_{23}
Zn	1.86 (1)	3.35 (2)	2.19 (1)	0	0.78 (1)	0
N_1	2.0 (1)	3.7 (1)	2.3 (1)	0.0 (1)	0.9 (1)	−0.1 (1)
N_2	2.0 (1)	3.8 (1)	2.6 (1)	0.2 (1)	1.0 (1)	0.2 (1)
N_3	2.6 (1)	8.2 (2)	4.6 (1)	0.4 (1)	1.8 (1)	0.7 (1)
N_4	4.2 (1)	6.0 (2)	2.5 (1)	0.5 (1)	0.5 (1)	−0.1 (1)
N_5	2.6 (1)	3.4 (2)	2.6 (1)	0	0.6 (1)	0
C_1	2.7 (1)	5.7 (2)	2.4 (1)	−0.2 (1)	1.0 (1)	0.0 (1)
C_2	2.7 (1)	5.7 (2)	2.7 (1)	−0.1 (1)	1.3 (1)	0.1 (1)
C_3	2.1 (1)	4.4 (2)	3.2 (1)	0.3 (1)	0.8 (1)	0.5 (1)
C_4	2.1 (1)	4.7 (2)	3.1 (1)	0.2 (1)	0.6 (1)	0.5 (1)
C_5	1.9 (1)	3.7 (1)	2.8 (1)	0.1 (1)	1.1 (1)	0.0 (1)
C_6	2.4 (1)	3.6 (1)	2.4 (1)	−0.1 (1)	0.8 (1)	0.3 (1)
C_7	2.3 (1)	4.1 (1)	2.3 (1)	0.0 (1)	0.9 (1)	−0.2 (1)
C_8	2.2 (1)	3.7 (1)	2.5 (1)	0.1 (1)	1.1 (1)	−0.1 (1)
C_9	2.0 (1)	3.5 (1)	2.6 (1)	0.1 (1)	0.9 (1)	−0.0 (1)
C_{10}	2.2 (1)	3.4 (1)	2.5 (1)	0.1 (1)	0.7 (1)	0.4 (1)
C_{11}	2.0 (1)	4.5 (1)	2.8 (1)	0.1 (1)	1.1 (1)	0.2 (1)
C_{12}	3.8 (2)	4.5 (2)	6.4 (2)	0.2 (1)	3.0 (2)	−0.2 (2)
C_{13}	4.0 (2)	6.1 (2)	6.8 (3)	1.3 (2)	3.3 (2)	0.6 (2)
C_{14}	3.7 (2)	8.0 (3)	7.3 (3)	−1.7 (2)	3.0 (2)	−1.5 (2)
C_{15}	3.8 (2)	6.0 (2)	7.0 (3)	−1.3 (2)	3.2 (1)	−1.6 (2)
C_{16}	2.5 (1)	2.5 (1)	2.4 (1)	0.2 (2)	0.9 (1)	0.2 (1)
C_{17}	3.4 (1)	4.1 (2)	3.2 (1)	−0.3 (1)	0.6 (1)	0.1 (1)
C_{18}	3.4 (1)	5.4 (2)	3.4 (1)	−0.5 (1)	0.6 (1)	−0.9 (1)
C_{19}	4.8 (2)	4.5 (2)	2.8 (1)	0.7 (1)	1.1 (1)	0.6 (1)
C_{20}	3.9 (1)	3.6 (1)	2.8 (1)	0.0 (1)	1.0 (1)	0.2 (1)
C_{21}	4.2 (2)	4.7 (2)	2.7 (1)	−0.2 (1)	0.9 (1)	−0.1 (1)
C_{22}	6.3 (2)	4.3 (2)	3.8 (2)	−0.4 (2)	1.5 (2)	−0.8 (1)
C_{23}	7.1 (4)	3.9 (2)	4.7 (3)	0	2.0 (3)	0

[a] Numbers in parentheses are the estimated standard deviations. The B_{ij} are related to the dimensionless β_{ij} employed during refinement as $B_{ij} = 4\beta_{ij}/a_i^*a_j^*$.

Table III. Parameters of the Hydrogen Atoms in the Unit Cell

Atom type[a]	Fractional coordinates[b] 10^3x	10^3y	10^3z	Thermal parameters, B, in Å²	
H_1	19	132	−126	3[c]	3 (1)[d]
H_2	185	134	−38	3	4 (1)
H_3	357	110	340	3	1 (1)
H_4	306	110	509	3	3 (1)
H_{12}	276	18	73	4	3 (1)
H_{13}	418	11	18	5	6 (1)
H_{14}	493	207	131	5	6 (1)
H_{15}	353	221	190	5	2 (1)
H_{17}	232	221	601	4	3 (1)
H_{18}	306	215	769	4	3 (1)
H_{19}	179	28	810	4	3 (1)
H_{20}	102	25	643	3	2 (1)
H_{21}	13	273	398	4	4 (1)
H_{22}	17	403	403	5	3 (1)
H_{23}	0	470	$^1/_4$	5	9 (4)

[a] Each hydrogen atom carries the same subscript as the carbon atom to which it is attached. [b] These coordinates, chosen to be consistent with the Fourier and difference synthesis, yield realistic C–H distances of ~1.0 Å. The positions of the H_{15}, H_{18}, and H_{23} atoms were ridiculously altered during the unfettered stage of refinement II. [c] Rounded-off isotropic thermal parameters of the associated carbon atoms. [d] The "refined" thermal parameters of the hydrogen atoms from II with associated standard deviations.

Table IV. Selected Interatomic Distances within the Molecule[a]

Type	Length, Å	Type	Length, Å	Type	Length, Å
Zn–N_1	2.067 (3)	N_5–C_{21}	1.335 (5)	C_6–C_{10}	1.413 (4)
Zn–N_2	2.079 (2)	C_1–C_2	1.349 (4)	C_6–C_{16}	1.493 (4)
Zn–N_5	2.143 (4)	C_1–C_7	1.453 (4)	C_{11}–C_{12}	1.395 (5)
N_1–Ax[b]	2.038 (3)	C_2–C_8	1.444 (4)	C_{11}–C_{15}	1.373 (5)
N_2–Ax[b]	2.056 (2)	C_3–C_4	1.361 (4)	C_{12}–C_{13}	1.392 (7)
N_1–C_7	1.366 (3)	C_3–C_9	1.444 (4)	C_{14}–C_{15}	1.395 (7)
N_1–C_8	1.373 (4)	C_4–C_{10}	1.445 (4)	C_{16}–C_{17}	1.396 (4)
N_2–C_9	1.374 (4)	C_5–Ax[b]	3.443 (3)	C_{16}–C_{20}	1.392 (4)
N_2–C_{10}	1.364 (3)	C_5–C_8	1.406 (3)	C_{17}–C_{18}	1.385 (4)
N_3–C_{13}	1.325 (6)	C_5–C_9	1.402 (4)	C_{19}–C_{20}	1.387 (4)
N_3–C_{14}	1.302 (7)	C_5–C_{11}	1.489 (4)	C_{21}–C_{22}	1.374 (5)
N_4–C_{18}	1.337 (5)	C_6–Ax[b]	3.452 (3)	C_{22}–C_{23}	1.384 (5)
N_4–C_{19}	1.328 (5)	C_6–C_7'	1.403 (4)		

[a] The number in parentheses following a parameter value is the estimated standard deviation in the last significant figure. [b] Symbol used for the twofold axis of the molecule.

in the inset to Figure 1) of the coordinated pyridine molecule. We consider first the stereochemistry of the porphine skeleton, as illustrated in Figures 2 and 3.

The displacements parallel to the twofold axis of the porphine skeletal atoms from the mean plane, as given in Figure 2, show that the methine carbon atoms (C_5, C_6, C_5', C_6') are virtually coplanar, but that the pyrrole rings are somewhat tipped out-of-plane, alternately up and down, to give the skeleton a quasi-D_{2d} type of ruffling. The accompanying small departure from planarity exhibited by the four nitrogen atoms introduces a slight perturbation into the essentially square-pyramidal coordination group around the zinc. In further agreement with the familiar fact that the porphine skeleton is rather easily deformed normal to the mean plane, it is seen from Table II that the skeletal atoms carry especially large values of the B_{22} thermal parameters corresponding to thermal vibrations of especially large magnitudes parallel to the twofold axis. The ruffling of the skeleton allows "local flatness" to be preserved in each pyrrole ring, the external bonds to methine carbon atoms included, and in each system of three bonds that radiate from a methine carbon

Table V. Bond Angles within the Molecule[a]

Angle	Value, deg	Angle	Value, deg	Angle	Value, deg
N_1ZnN_2	88.8 (1)	$C_8C_5C_{11}$	116.4 (3)	$N_2C_{10}C_6$	125.6 (2)
N_1ZnN_2'	88.3 (1)	$C_9C_5C_{11}$	117.9 (2)	$C_4C_{10}C_6$	124.5 (2)
ZnN_1C_7	126.3 (2)	$C_7'C_6C_{10}$	124.8 (2)	$C_{12}C_{11}C_{15}$	116.7 (3)
ZnN_1C_8	125.6 (2)	$C_7'C_6C_{16}$	117.7 (3)	$C_{11}C_{12}C_{13}$	119.2 (4)
$C_7N_1C_8$	106.5 (2)	$C_{10}C_6C_{16}$	117.5 (2)	$N_3C_{13}C_{12}$	123.6 (4)
ZnN_2C_9	126.3 (2)	$N_1C_7C_1$	109.6 (2)	$N_3C_{14}C_{15}$	124.6 (4)
ZnN_2C_{10}	126.8 (2)	$N_1C_7C_6'$	126.0 (3)	$C_{11}C_{15}C_{14}$	119.2 (4)
$C_9N_2C_{10}$	106.7 (2)	$C_1C_7C_6'$	124.4 (2)	$C_{17}C_{16}C_{20}$	117.2 (3)
$C_{13}N_3C_{14}$	116.7 (4)	$N_1C_8C_2$	109.9 (2)	$C_{16}H_{17}C_{18}$	119.3 (3)
$C_{18}N_4C_{19}$	116.4 (3)	$N_1C_8C_5$	125.8 (3)	$N_4C_{18}C_{17}$	123.8 (3)
$C_{21}N_5C_{21}'$	118.0 (4)	$C_2C_8C_5$	124.4 (3)	$N_4C_{19}C_{20}$	124.5 (3)
$C_2C_1C_7$	107.0 (3)	$N_2C_9C_3$	109.8 (2)	$C_{16}C_{20}C_{19}$	118.8 (3)
$C_1C_2C_8$	107.0 (3)	$N_2C_9C_5$	125.4 (2)	$N_5C_{21}C_{22}$	123.0 (3)
$C_4C_3C_9$	106.7 (3)	$C_3C_9C_5$	124.8 (3)	$C_{21}C_{22}C_{23}$	118.5 (4)
$C_3C_4C_{10}$	107.0 (2)	$N_2C_{10}C_4$	109.9 (3)	$C_{22}C_{23}C_{22}'$	119.1 (5)
$C_8C_5C_9$	125.5 (3)				

[a] The number in parentheses following a parameter value is the estimated standard deviation in the last significant figure. Primed symbols denote atoms derived from those listed in Table I by the operation of the twofold axis.

atom; the mean deviation from exact planarity in no case exceeds 0.01 Å. Such preservation of local flatness also is observed with the much more pronounced ruffling of S_4 type that characterizes the porphine skeleton in tetragonal crystals of tetraphenylporphine[25] (hereafter written H_2TPP_{te}) and its Cu(II) and Pd(II) derivatives[8] (CuTPP and PdTPP). Indeed, the rather generally observed departures from planarity that may be required of the porphine skeleton by packing constraints in crystalline porphyrins seem largely to be absorbed in small rotations about the bonds connecting the inherently flat subgroupings of atoms (or bond systems) and in quite modest alterations in bond angles. To identify the energetically more consequential strain that appears as objectively significant alterations in the skeletal bond lengths, we must compare metalloporphyrins in which extreme values of the complexing M–N bond lengths are utilized (*vide infra*).

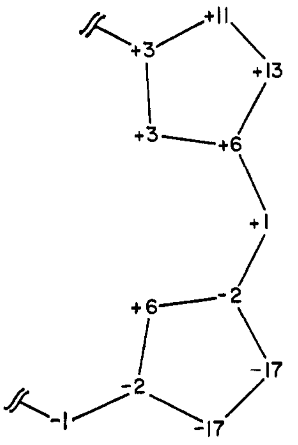

Figure 2. Diagram to illustrate the ruffling in the right-hand half (the asymmetric unit) of the porphine skeleton as seen in Figure 1. The perpendicular displacements, in units of 0.01 Å, of the atoms from the mean plane replace the symbols for these atoms as carried in Figure 1.

Inasmuch as the pyridyl rings (each flat to within 0.01 Å) are rotated about the C_5–C_{11} and C_6–C_{16} bonds (Figure 1) so as to make very large dihedral angles of 65 and 59°, respectively, with the mean plane of the porphine skeleton, it appears that delocalization of π bonding is largely cut off at the bridging bonds. Further support of this conclusion is provided by C_5–C_{11} and C_6–C_{16} lengths (1.49 Å) that are characteristic of essentially pure σ bonding in trigonal sp^2 hybridization.

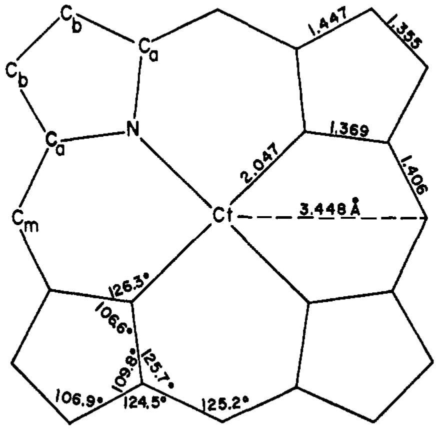

Figure 3. Diagram giving the averaged (D_{4h}) bond lengths (Å) and angles (deg) in the porphine skeleton of the PyZnTPyP molecule. Averaged values for the important Ct–N and Ct–C_m radii also are given. The weighted esd of the mean is 0.003 Å for the C_b–C_b distance, and is 0.002 Å for all other distances shown on the diagram. Not shown is the Zn–N bond length to porphine nitrogen atoms of 2.073 (2) Å (see Figure 4). The symbolism used for the three classes of carbon atoms is maintained in Table VI and in the discussion thereof.

The C–C and C–N bond lengths within the porphine skeleton of the PyZnTPyP molecule exhibit no objectively significant deviations from the highest class of fourfold symmetry; indeed, the mean deviation from the averaged length for each chemical type of bond is always somewhat smaller than the smallest of the standard deviations estimated for the individual bond lengths of the type. Averaged bond lengths for the several chemical types, each carrying its formally estimated standard deviation from the mean, are entered on Figure 3; C_a and C_b are used for the respective α and β atoms of the

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[25] M. J. Hamor, T. A. Hamor, and J. L. Hoard, *J. Amer. Chem. Soc.*, 86, 1938 (1964).

pyrrole rings, C_m for methine carbon. Also entered on Figure 3 are the averaged radii, Ct–N and Ct–C_m, extending from the skeletal center (Ct) to the respective pyrrole nitrogen and methine carbon atoms.

Distances in the porphine skeleton carried on Figure 3 are listed in the second column of Table VI for comparison with the analogous data, listed as averages in each of the three categories of columns 3–5, from eight structure determinations for crystalline porphyrins. The distribution of the metalloporphyrins among the categories of columns 2, 3, and 4 is determined by the value of the Ct–N radius—not by the complexing M–N bond length; M–N > Ct–N in PyZnTPyP and in the three high-spin iron(III) porphyrins that are included in column 4. Column 3 carries the averaged distances that characterize the porphine skeleton in the Ni(II) derivative of 2,4-diacetyldeuteroporphyrin IX dimethyl ester[3] (hereafter written NiDeut); the Ct–N = Ni–N = 1.960 (4) Å distance is a minimum for known metalloporphyrin structures, and the precision of the averaged bond data approaches that attained for the PyZnTPyP molecule. Column 4 carries averaged data from chlorohemin,[26] the methoxyiron(III) derivative of mesoporphyrin IX dimethyl ester[27] (MeOFeMeso), the chloroiron(III) derivative of tetraphenylporphine[6] (ClFeTPP), and PdTPP.[8] Averaging the distances of interest for this group of porphyrins, wherein $2.008 \lesssim$ Ct–N $\lesssim 2.022$ Å, is a means for achieving statistical significance; all three iron porphyrins are subject to some degree of orientational disorder of the molecules in the crystals, and the X-ray data for crystalline PdTPP are of rather too limited scope and quality for the very precise delineation of the positions of the lighter atoms.

Table VI. Averaged Parameters of the Porphine Skeleton in Porphyrins as a Function of the Radius of the Central Core (Ct–N)[a]

Type of distance	Length, Å, in PyZnTPyP	NiDeut	Fe and Pd derivatives[b]	Metal-free porphyrins[c]
Ct–N	2.047 (2)[d]	1.960 (4)[d]	2.013[e]	2.057[e]
N–C_a	1.369 (2)	1.383 (3)	1.384	1.362
C_a–C_m	1.406 (2)	1.375 (4)	1.389	1.397
Ct–C_m	3.448 (2)	3.402 (4)	3.425	3.426
C_a–C_b	1.447 (2)	1.447 (3)	1.449	1.441
C_b–C_b	1.355 (3)	1.350 (5)	1.358	1.352

[a] Ct is used for the centroid of the grouping of four porphine nitrogen atoms. [b] Chlorohemin, MeOFeMeso, ClFeTPP, and PdTPP wherein the ostensible value of Ct–N ranges from 2.008 to 2.022 Å. [c] H_2TPP_{te}, H_2TPP_{tr}, and porphine wherein Ct–N ranges from 2.051 to 2.065 Å. [d] The figure in parentheses is the weighted standard deviation of the mean in units of 0.001 Å. [e] Averaged value for the several compounds.

Comparing the data for NiDeut and PyZnTPyP, we see that an increase of 0.087 (4) Å in the Ct–N radius is accompanied by an increase of 0.046 (4) Å in the Ct–C_m radius, an increase of 0.031 (4) Å in the C_a–C_m bond length, and a decrease of 0.014 (4) Å in the N–C_a distance. The significantly affected quantities are those that would be particularly sensitive to a varying Ct–N radius in a purely mechanical model of the skeleton. We further note that the CuTPP molecule, wherein Ct–N = Cu–N = 1.981 (7) Å, carries reported values[8] of these three sensitive distances that differ immaterially from those in NiDeut. The Ct–C_m and C_a–C_m distances in the metalloporphyrins of column 4, with a Ct–N radius of ~2.01 Å, lie each about halfway between the corresponding values in the NiDeut and PyZnTPyP molecules, whereas the less sensitive N–C_a bond length is objectively indistinguishable from that in the nickel porphyrin.

The free base molecules in the last column of Table VI, tetraphenylporphine as it exists in the tetragonal[25] and triclinic[28] crystalline modifications (H_2TPP_{te} and H_2TPP_{tr}, respectively) and porphine[29] itself, constitute a distinctive category in which the especially large Ct–N radius of 2.057 Å results from the mutual repulsions of the two hydrogen atoms carried by the central grouping of four nitrogen atoms.[30] In view of this special feature, we might expect that the effects of the expanded Ct–N radius would appear in a more pronounced contraction of the N–C_a bond length and rather less expansion of the C_a–C_m and Ct–C_m distances than in the PyZnTPyP molecule. This pattern of differences is followed in the data of Table VI, but with objective significance only for the Ct–C_m distance. There are reasons,[30,31] however, for supposing that the most pertinent comparison is with the data reported for the H_2TPP_{te} molecule in which Ct–N = 2.054 (4), N–C_a = 1.350 (5), C_a–C_m = 1.399 (5), and Ct–C_m = 3.413 (5) Å; such comparison rather enhances the probability that the N–C_a bond length is significantly shorter in the free base of real or effective fourfold symmetry than it is in the zinc porphyrin.

Still larger Ct–N radii (~2.11 Å), accompanied by very severe rufflings and other deformations of the porphine skeletons, are reported for the porphyrin diacids, H_4TPP^{2+} and H_4TPyP^{2+}, that result from the protonation of tetraphenylporphine and tetra(4-pyridyl)porphine.[32] The precision realized in the difficult structure determinations for the crystals in which these cationic species were studied is not conducive to detailed comparisons of structural parameters with those listed in Table VI.

Of subsequent interest is the fact that the Ni–N = Ct–N bond length of 1.960 (4) Å in NiDeut is substantially longer than is normal for diamagnetic square-planar Ni(II) in the absence of severe stereochemical constraints. Thus with decreasing severity of such constraints in the diamagnetic bis(N-alkylsalicylaldi-

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(26) D. F. Koenig, *Acta Crystallogr.*, 18, 663 (1965).

(27) J. L. Hoard, M. J. Hamor, T. A. Hamor, and W. S. Caughey, *J. Amer. Chem. Soc.*, 87, 2312 (1965).

(28) S. J. Silvers and A. Tulinsky, *ibid.*, 89, 3331 (1967).

(29) L. E. Webb and E. B. Fleischer, *J. Chem. Phys.*, 43, 3100 (1965).

(30) The reality of these repulsions is vividly displayed in the H_2TPP_{tr} molecule wherein the separation of the diagonally opposed pair of nitrogen atoms that carry the hydrogen atoms is 0.14 Å greater than that of the other diagonal pair that carry no hydrogen.[28] The markedly rhombic form of the skeletal core makes it questionable whether the averaged Ct–N and N–C_a distances of 2.065 and 1.370 Å, respectively, are appropriately included in the more general averages of column 5. In the tetragonal H_2TPP_{te} and quasitetragonal porphine molecules, by contrast, each nitrogen atom carries a well-defined "half-hydrogen" atom as the presumed statistical consequence of proton jumps.

(31) The reported contamination of the porphine crystal by a small concentration of what was presumed to be the copper derivative would be expected to give apparent values of the Ct–N and N–C_a distances that were, respectively, a bit small and a bit large; experimental values of 2.051 and 1.366 Å were obtained.[29]

(32) A. Stone and E. B. Fleischer, *J. Amer. Chem. Soc.*, 90, 2735 (1968).

minato)nickel(II) complexes,[33] the Ni–N bond length decreases from 1.92 to 1.85 Å. Especially pertinent to the subsequent discussion of the complexing bonds in the PyZnTPyP molecule is the Ni–N distance of 1.897 (3) Å in the tetrakis(3,4-dimethylpyridine)nickel(II) cation,[34] a value of 0.06 Å below the Ni–N distance in NiDeut. These comparisons and the fact that the Ni(II) porphyrins are particularly stable representatives of the class suggest that in no metalloporphyrin is the complexing M–N distance likely to fall significantly below the 1.960 (4) Å in NiDeut.[35]

The averaged bond lengths and other pertinent dimensions of the square-pyramidal coordination group in the PyZnTPyP molecule are displayed on the diagram of Figure 4. Although the averaged length[36] of the complexing bonds to porphine nitrogen atoms differs almost trivially from the averaged value (2.068 Å) for the Fe–N distance in the chlorohemin and MeOFe-Meso molecules, there are rather striking quantitative differences in several of the other stereochemical parameters. The out-of-plane displacement of the zinc atom (0.33 Å) is only about two-thirds that of the iron atom (0.48 Å). The complexing bond to the pyridine molecule is about 0.070 Å longer than the bonds to porphine nitrogen, whereas the bond to the axial ligand in each of the high-spin iron porphyrins is as short as, or even shorter than, the value expected with low-spin iron(III); indeed, the Fe–Cl and Fe–O bond lengths of 2.21 and 1.84 Å, respectively, suggest an Fe–N bond distance of ~1.90 Å to an axially coordinated pyridine molecule in a square-pyramidal high-spin Fe(III) porphyrin.[37] The N···N separation between axial and basal ligands in the PyZnTPyP molecule of 3.21 Å is well above the van der Waals packing diameter[38] of 3.0 Å; with, moreover, the same bond distances and exact centering of the Zn(II) atom in the plane, this N···N separation would drop only to 2.97 Å—a value not indicative of excessively tight packing. Thus it is evident that nonbonding repulsions of the pyridine for the porphine nitrogen atoms cannot account either for the refusal of the PyZnTPyP molecule to complex a second axial ligand[5] or for the substantially greater length of the axial Zn–N bond in the five-coordinate species.

The axial bond enjoys virtually exclusive use of the $4p_z$ orbital of the Zn(II) atom, it shares most generously in the 4s orbital, and it is oriented to take full advantage of whatever bonding capacity the higher lying $4d_{z^2}$, d_{xz}, and d_{yz} orbitals may afford; this bond, consequently, can scarcely be regarded either as unduly long or improbably weak. Rather must it be that the complexing bonds to porphine nitrogen atoms in PyZnTPyP—and in the high-spin iron porphyrins as well—are anomalously short in the same sense that the Ni–N bonds in NiDeut are anomalously long. By reason of its charge distribution and structure, the porphinate anion is endowed with formidable complexing power toward a variety of cations, large and small, but the quasirigidity of the porphine skeleton toward undue expansion or contraction requires these cations to accept complexing bond lengths within a very much narrowed range relative to that which applies with monodentate nitrogen ligands.[39] Just as it is improbable that the Ct–N radius can fall below the 1.96 Å in NiDeut, it seems most unlikely that it can exceed the ~2.11 Å observed in the severely ruffled, difficultly preparable H_4TPP^{2+} and H_4TPyP^{2+} diacids.[32] This does not mean that the complexing bond length may not exceed 2.11 Å even though the Ct–N distance be limited to a more probable range of values below 2.11 Å; noting that a Ct–N radius of 2.06 Å in combination with an out-of-plane displacement of the metal atom of 0.60 Å leads to 2.15 Å for the M–N bond length, it is seen that metalloporphyrins of modest stability can be formed by overlarge, weakly complexing, metal ions in either five or four coordination. In a tin(IV) porphyrin, on the other hand, we expect the strongly complexing metal atom to be centered in the plane with a Ct–N = Sn–N distance below 2.11 Å, even though the sum of the covalent radii[38] for nitrogen and octahedral tin(IV) is 2.15 Å. A precise value for this bond length will soon be available from a structure determination in progress for an excellent crystal of Cl_2SnTPP.

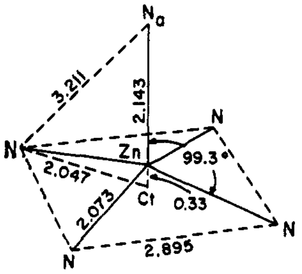

Figure 4. The idealized (C_{4v}) geometry and averaged dimensions (Å) of the square-pyramidal coordination group in the PyZnTPyP molecule.

A useful datum to have for reference is the value of the Ct–N radius that corresponds more or less exactly to minimization of strain in the porphine skeleton. That this datum lies between the 1.960 Å of NiDeut and the 2.047 Å of PyZnTPyP and that it is in the range of 2.01–2.02 Å is supported by the evidence educed below.

The absence of thermodynamic evidence for the addition of a second axial ligand to the PyZnTPyP molecule[5,40] shows that the zinc ion is not centered in the plane of the nitrogen atoms for any measurable fraction

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[33] E. C. Lingafelter and R. L. Braun, *J. Amer. Chem. Soc.*, **88**, 2951 (1966).

[34] F. Madaule-Aubry, W. R. Busing, and G. M. Brown, *Acta Crystallogr.*, **B24**, 754 (1968).

[35] This conclusion applies only to the true porphyrins, not to modified cyclic tetrapyrroles such as the corrin ring system.

[36] The small difference in the lengths of the two structurally nonequivalent classes of complexing bonds to porphine nitrogen represents the only objectively probable effect on bond lengths of the quasi-D_{2d} ruffling of the porphine skeleton (*vide supra*). The complexing bonds, as the weakest links, afford the principal repository for accumulated strain.

[37] These short axial bonds are readily interpreted as follows.[4,8] The $3d_{z^2}$ orbital of high-spin Fe^{3+} combines with the appropriate σ-type orbital of the axial ligand to give a strongly bonding orbital that accepts the donor electron pair and a nonbonding (or weakly antibonding) orbital that accommodates the unpaired electron; the 4s and $4p_z$ orbitals of Fe^{3+} can also contribute to the bonding. It appears that the higher lying $4d_{z^2}$ orbital of Zn(II) cannot be used to comparable advantage in otherwise similar circumstances.

[38] L. Pauling, "The Nature of the Chemical Bond," 3rd ed, Cornell University Press, Ithaca, N. Y., 1960.

[39] Even more striking examples of this general phenomenon are provided by the higher borides of the metals wherein lattice parameters and M–B separations are largely determined by three-dimensional boron frameworks, substantial variations in the metallic (or ionic) radii notwithstanding. *Cf.* J. L. Hoard and R. E. Hughes in "The Chemistry of Boron and Its Compounds," E. L. Muetterties, Ed, John Wiley & Sons, Inc., New York, N. Y., 1967, pp 25–154.

[40] C. H. Kirksey, P. Hambright, and C. B. Storm, *Inorg. Chem.*, **8**, 2141 (1969), observe only 1:1 complexing of ten substituted pyridine derivatives with ZnTPP.

of the complexed species that exist in solution; indeed, it shows that the interaction of a potentially sixth ligand with the five-coordinate complex at a Zn···N distance >2.40 Å is too weak to give detectable evidence of additional loose complexing.[41] Although the small magnitude of the displacement out-of-plane of the zinc ion is a tribute to the latent preference of this ion for an octahedral bonding pattern, the persistence of this displacement and the accompanying small expansion of the porphine skeleton provide full recognition of the constraints imposed by the skeleton.

By reason of the overlong Fe–N bonds, the high-spin Fe^{3+} ion in a porphyrin also is constrained to lie out-of-plane, but its capacity to form an extraordinarily short and stable bond with a *single* axial ligand gives it a distinctive preference for five coordination. The complexing bonds to porphine nitrogen are well-characterized in first approximation as essentially ionic, with accompanying angles that are very easily strained by quite minor stresses.[4] The comparatively large out-of-plane displacement of the high-spin Fe^{3+} ion (~0.48 Å) results from this adaptability of the bond angles to the constraints imposed by the porphine skeleton, and the data from MeOFeMeso and chlorohemin suggest that a Ct–N radius of 2.01–2.02 Å is small enough to minimize skeletal stain.[4]

Particularly severe steric interactions in the planar four-coordinate complexes of palladium(II) may lead to Pd–N bond lengths as large as 2.06 Å,[42] but the more usual values (with mixed N and O ligands) lie between 1.99 and 2.02 Å. The larger 2.02 Å value is much the more probable with monodentate all-nitrogen ligands. It thus appears that the Pd–N bond length of 2.009 (9) Å in PdTPP[8] is very nearly the value of the Ct–N radius that simultaneously best suits the complexing bonds and minimizes strain in the porphine skeleton.

In the octahedral coordination group of the low-spin bis(imidazole)tetraphenylporphinatoiron(III) cation as observed in the crystalline chloride, the lengths of the four Fe–N bonds to porphine nitrogen atoms average 1.989 (2) Å, while the lengths of the axial bonds are 1.957 (4) and 1.991 (5) Å. It is pointed out, however, that the lower (1.95–1.96 Å) value appears to be appropriate for both axial ligands in the unstrained complex.[43] Lacking the skeletal constraints, one would expect the complexing bonds to the charged porphine nitrogen atoms to be certainly as short as, probably shorter than, the bonds to imidazole nitrogen; consequently, it appears that a Ct–N radius >1.99 Å is required to minimize skeletal strain. That the shortening of the Ct–N radius from the 2.01–2.02 Å corresponding to minimum skeletal strain is only half or less of that in NiDeut is attributable to the addition in the iron porphyrin of eight very tight N···N packing distances (2.79 Å) between the axial and equatorial nitrogen atoms that are fully 0.20 Å below the van der Waals packing diameter.[38] The M–N bond lengths cited for the low-spin Fe(III) porphyrin presumably apply with little or no alteration to the corresponding cobalt(III) derivative; for although Pauling's octahedral low-spin bond lengths,[38] 1.91 and 1.92 Å for Fe–N and Co–N, respectively, are clearly too small when all six bonds are directed to nitrogen atoms, near isodimensionality of isostructural Fe(III) and Co(III) complexes should be maintained. The averaged Co–N bond length of 1.96–1.97 Å from structure determinations for Co(III) complexes utilizing only monodentate nitrogen ligands[44] presumably must be slightly increased in a porphyrin by reason of the anticipated stretching of the four equatorial bonds to a value $\gtrsim$1.99 Å.

The earlier report on the refinement of the $H_2OZnTPP$ crystalline arrangement[7] emphasized that the available X-ray data could not give a quantitatively definitive resolution of the grossly overlapped "half-atoms" of zinc in the disordered structure, and it was suggested that the apparent length of 2.20 Å for the axial Zn–OH_2 bond was unduly long because the out-of-plane displacement of the zinc atom was underestimated at 0.19 Å. If we carry over the 0.33 Å out-of-plane displacement of the zinc atom from the PyZnTPyP molecule to the $H_2OZnTPP$ species, we obtain Zn–OH_2 = 2.06 Å, a bond length quite in accord with expectation.

For appraisal of both the similarities and the differences displayed by magnesium and zinc porphyrins, we make limited use of Mg–N bond lengths from a structure determination long in progress[45] for crystals of the dipyridinemagnesium(II) derivative of etioporphyrin-II ($Py_2MgEtio$). Although the highly disordered crystalline arrangement does not lend itself to the very precise evaluation of the Mg–N distances in the octahedral coordination group, it appears that the averaged Mg–N bond length to porphine nitrogen atoms does not exceed 2.05 Å, whereas the averaged length of the axial bonds to the pyridine molecules is ~2.34 Å, ~0.20 Å longer than the axial bond in PyZnTPyP. The eight separations of ~3.09 Å between axial and equatorial nitrogen atoms, as compared with just four such distances of 3.21 Å in the pyramidal coordination group of the PyZnTPyP molecule, are not much longer than the van der Waals diameter of nitrogen (3.0 Å). The inherent weakness of the axial bonds is manifest in these data as also in the very small equilibrium constant for the addition of the second pyridine molecule,[5] ~0.58 at 29.9°.

The cited structural data together with the large ratio of the first and second equilibrium constants for the stepwise addition of pyridine to MgTPP[5] ($\sim 3 \times 10^4$ at 29.9°) tell us that the monpyridinemagnesium complex owes its stability to a square-pyramidal coordination group that is conducive to the relatively firm attachment of a single axial ligand. Anticipated modifications in the coordination group described for the PyZnTPyP molecule that should apply in the corresponding monopyridinemagnesium species (and correlate with its lesser stability toward the loss of pyridine[5]) are a smaller out-of-plane displacement of the Mg^{2+} ion in association with slightly shorter complexing bonds to the charged porphine nitrogen atoms, but a significantly longer bond to the electrically neutral pyridine

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(41) These observations further suggest that the zinc must lie somewhat out-of-plane in the four-coordinate ZnTPyP species.

(42) V. W. Day, M. D. Glick, and J. L. Hoard, *J. Amer. Chem. Soc.*, **90**, 4803 (1968). Note that the steric interactions in the corresponding Ni(II) complex force the Ni(II) atom into tetrahedral coordination.

(43) R. Countryman, D. M. Collins, and J. L. Hoard, *ibid.*, **91**, 5166 (1969). The longer axial bond is associated with a sterically unfavorable orientation of the imidazole ligand whereby its critical pair of hydrogen atoms—those of the C–H bonds adjacent to the complexed nitrogen atom—enter into strong repulsive interaction with the porphine skeleton. The unfavorable orientation of this ligand is attributable solely to packing constraints in the crystal.

(44) *Cf.* F. A. Cotton and W. T. Edwards, *Acta Crystallogr.*, **B24**, 474 (1968).

(45) D. M. Collins and R. Countryman, in this laboratory.

ligand.[46] The formation of a shorter, more stable, axial bond in the zinc porphyrin is favored by the superior capacity of the Zn^{2+} ion for covalent binding of the pyridine molecule and, in minor degree, by the lessened importance of nonbonding repulsions that is associated with the larger out-of-plane displacement of the cation. The recently published structure determination for crystalline $H_2OMgTPP$[47] leads to a five-coordination group that, with the substitution of a water for a pyridine molecule as the axial ligand, follows the anticipated pattern.

(46) Reversal in the magnitudes of the Zn–X and Mg–X bond lengths, depending on whether the ligands are neutral or carry negative charge, is readily identified in isostructural zinc and magnesium compounds that crystallize in particularly simple structural types. In the fluorides and chlorides the Mg–X bonds are significantly shorter, whereas in the hexaaquo cations in the $M(OH_2)_6SiF_6$ structural type it is the $Zn–OH_2$ bonds that are shorter. Thus the less covalently (or more ionically) inclined Mg^{2+} ion allows itself to be "squeezed" into plane within a not very stable six-coordinate porphyrin ($Py_2MgEtio$) whereas Zn^{2+} does not.

(47) R. Timkovich and A. Tulinsky, *J. Amer. Chem. Soc.*, **91**, 4430 (1969). The precision of parameter determination was limited by the fact that $H_2OMgTPP$ crystallizes in the same disordered structural type as do ClFeTPP[6] and $H_2OZnTPP$.[7]

Syntheses of Actinomycin and Analogs. III. A Total Synthesis of Actinomycin D (C_1) *via* Peptide Cyclization between Proline and Sarcosine[1-3]

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Abstract: A synthesis of actinomycin D (C_1) is described in which the key reaction, cyclization of the pentapeptide lactone, was carried out by peptide bond formation between proline and sarcosine using the *p*-nitrophenyl ester activation. The ester bond between the carboxyl group of N-methylvaline and the hydroxyl group of threonine was formed by a reaction of *t*-butyloxycarbonyl-L-threonine with the mixed anhydride from benzyloxycarbonyl-L-N-methylvaline and isobutyl chloroformate. Several protected peptide intermediates were readily purified by chromatography on Sephadex LH-20 in methanol which fractionated complex reaction mixtures efficiently. The synthetic actinomycin was indistinguishable from natural material in its physical properties and its biological activities.

Actinomycins are a group of closely related peptide antibiotics.[4] Actinomycins D (C_1)[5] and C_3, of known structure[6] (Figure 1), are important as highly effective chemotherapeutics in the treatment of Wilms' tumor,[7] trophoblastic tumors,[8] and rhabdomyosarcoma.[9] Their very high cytotoxicity[10] and their inactivity toward some tumors have prompted the search for modified actinomycins with improved therapeutic indices and with broader antitumor activities. However, none of the naturally occurring variants[4] and none of the many derivatives which have been prepared by substitution at the 2 and 7 positions[11,12] of the phenoxazinone moiety have shown promise.[13] Since the peptide moieties play important roles in the action of actinomycins[14] and control the unusual solubility characteristics,[15] possibly important in cell membrane permeation, we decided to prepare peptide analogs by total synthesis. An efficient pathway was required for this program by which analogs could be prepared in sufficient quantities for comprehensive biological testing.

(1) A preliminary communication has been published: J. Meienhofer, *Experientia*, **24**, 776 (1968), part II in this series.

(2) Part I: J. Meienhofer, *J. Org. Chem.*, **32**, 1143 (1967).

(3) Abbreviations follow the rules of the IUPAC–IUB Commission on Biochemical Nomenclature, in *Biochemistry*, **5**, 1445, 2485 (1966); **6**, 362 (1967); *J. Biol. Chem.*, **241**, 2491 (1966). Threonine, proline, and N-methylvaline are of L configuration; valine is of D configuration. This work was supported by Public Health Service Research Grants (No. C-6516 from the National Cancer Institute, No. FR-05526 from the Division of Research Facilities and Resources), National Institutes of Health, by A. and M. Lasker Foundation, New York, and A. T. and V. D. Fuller Cancer Research Unit Grant, American Cancer Society (Massachusetts Division), Inc.

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