Resonance Raman Spectra of Dioxygen Adducts of Cobalt Picket Fence Porphyrins

J. Odo,[1a] H. Imai,[1b] E. Kyuno,[1b] and K. Nakamoto*[1a]

*Contribution from the Department of Chemistry, Marquette University, Milwaukee,
Wisconsin 53233, and Department of Pharmaceutical Science, School of Pharmacy,
Hokuriku University, 3 Ho Kanagawa-machi, Kanazawa 920-11, Japan. Received May 4, 1987*

Abstract: The resonance Raman (RR) spectra (406.7-nm excitation, ca. –90 °C) of dioxygen adducts of atropisomers of picket fence porphyrins, $Co(T_{piv}PP)(B)O_2$ and $Co(T_{neo}PP)(B)O_2$, were measured in toluene with a variety of base ligands (B). The internal mode of the solvent (toluene) was resonance-enhanced when the picket fence has a "semiprotected" cavity (e.g., α^3- and α^2-atropisomers) and when the $\nu(O_2)$ is matched closely to the frequency of toluene by choosing a proper base ligand. These observations confirmed our previous notion that vibrational energy transfer can occur when the bound dioxygen is directly associated with the solvent molecule and the frequency matching condition is satisfied. The marked low-frequency shift of the $\nu(O_2)$ in going from $Co(\alpha^4-T_{piv}PP)(B)O_2$ to the corresponding $Co(\alpha^4-T_{neo}PP)(B)O_2$ was attributed to the strengthening of the N—H⋯O_2 hydrogen bond between the o-acetamido NH group of the picket fence and the bound dioxygen in the latter complex. When the NH protons of the o-acetamido groups of $Co(\alpha^4-T_{neo}PP)(4-PhPy)O_2$ were deuteriated, the $\nu(Co-O_2)$ at 520 cm^{-1} and $\delta(CoOO)$ at 267 cm^{-1} were shifted 2–3 cm^{-1} to lower frequencies. The $\nu(O_2)$ of $Co(\alpha^4-T_{neo}PP)(1-MeIm)O_2$ at 1137 cm^{-1} was shifted to 1142 cm^{-1} when the temperature was raised from ca. –90 °C to room temperature. These observations provided further support for the N—H(o-acetamido)⋯O_2 bonding proposed by other workers. The $\nu(O_2)$ of eleven modified picket fence porphyrins were measured to examine the effect of changing the picket structure on such hydrogen bonding. In all cases, the $\nu(O_2)$ of these compounds were observed between those of $Co(\alpha^4-T_{piv}PP)(B)O_2$ (1148 cm^{-1}) and $Co(\alpha^4-T_{neo}PP)(B)O_2$ (1137 cm^{-1}) (B = 1-MeIm). It was concluded that the major factor in determing the $\nu(O_2)$ of these picket fence porphyrins is the strength of the N—H(o-acetamido)⋯O_2 bond which varies in a subtle manner depending upon the size and shape of the picket. Introduction of protic groups such as OH and NH_2 in the picket gave only small low-frequency shifts of $\nu(O_2)$ relative to those having no protic groups. These results suggest that "protected porphyrins" other than picket fence type porphyrins must be employed to mimic bound O_2 in native heme cavities more closely.

Recently, a number of model compounds have been synthesized to mimic biological functions of hemoglobin (Hb) and myoglobin (Mb). In 1975 Collman et al.[2] first prepared the picket fence porphyrin $Fe(T_{piv}PP)$, which can reversibly bind O_2 in the presence of a base ligand (B) at room temperature. Since then, the structural and bonding properties of its dioxygen adducts, $Fe(T_{piv}PP)(B)O_2$, and its Co(II) analogues have been studied extensively by using a variety of physicochemical methods.[3] As to vibrational spectra, Collman and co-workers[4] first located the $\nu(O_2)$ of these adducts at 1163–1150 cm^{-1} in IR spectra. Caughey et al.[5a] observed two oxygen-isotope-sensitive bands at 1155 and 1107 cm^{-1} in the IR spectrum of HbO_2 and Alben et al.[5b] attributed its origin to Fermi resonance between the unperturbed $\nu(O_2)$ (~1135 cm^{-1}) and the first overtone of the $\nu(Fe-O_2)$ (2 × 567 cm^{-1}). Later, Tsubaki and Yu[6] observed three oxygen-isotope-sensitive bands at ~1153, ~1137, and ~1103 cm^{-1} in the resonance Raman (RR) spectra of $CoHbO_2$ and $CoMbO_2$; they attributed the latter two bands to resonance interaction between a porphyrin mode at 1123 cm^{-1} and the $\nu(O_2)$ at ~1122 cm^{-1}, which originates in the O_2 adduct hydrogen bonded to the distal histidine, and the first band at ~1153 cm^{-1} to the $\nu(O_2)$ of the O_2 adduct which is free from such hydrogen-bonding interaction. The fact that the latter frequency is close to that of the picket fence porphyrins was regarded as evidence to support their assignments. The appearance of two oxygen-isotope-sensitive bands (1158 and 1144 cm^{-1}) in the RR spectrum of Co-

Chart I

α^4 α^3

cis-α^2 trans-α^2

R = CH_2-C(CH_3)$_3$, TneoPP

R = C(CH_3)$_3$, TpivPP
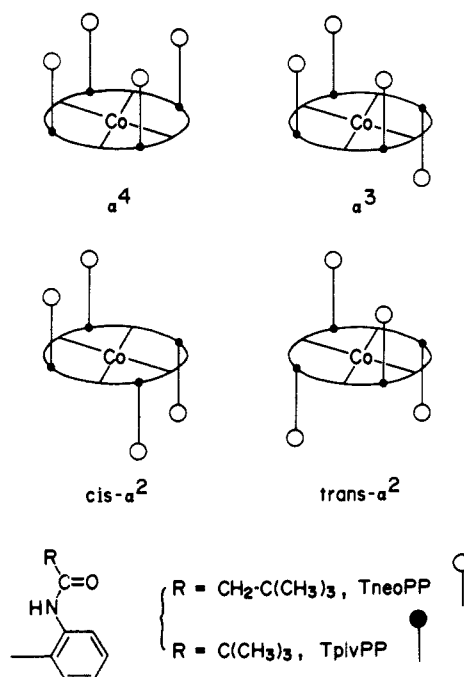
$(T_{piv}PP)(1,2-DiMeIm)O_2$ was also attributed to the equilibrium mixture of two conformers although their structures were not known.[7]

The nature of bound O_2 inside the picket fence is governed by several factors including the size, shape, and polarity of the pocket, and its interaction with the protic group of the picket. The main objectives of this investigation are threefold. First, we will study how the bound O_2–solvent (toluene) interaction varies in a series of atropisomers shown in Chart I. We[8] observed previously that

(1) (a) Marquette University. (b) Hokuriku University.
(2) Collman, J. P.; Gagne, R. R.; Reed, C. A.; Halbert, T. R.; Lang, G.; Robinson, W. T. *J. Am. Chem. Soc.* **1975**, *97*, 1427.
(3) Collman, J. P.; Halbert, T. R.; Suslick, K. S. *O₂ Binding to Heme Proteins and their Synthetic Analogs*, In *Metal Ions in Biology*; Spiro, T. G., Ed.; John Wiley: New York, 1980; Vol. 2, p 1.
(4) Collman, J. P.; Brauman, J. I.; Halbert, T. R.; Suslick, K. S. *Proc. Natl. Acad. Sci. U.S.A.* **1976**, *73*, 3333.
(5) (a) Caughey, W. S.; Choc, M. G.; Houtchens, R. A. *Biochemical and Clinical Aspects of Oxygen*; Caughey, W. S., Ed.; Academic: New York, 1978; pp 4 and 18. (b) Alben, J. O.; Bare, G. H.; Moh, P. P. *Biochemical and Clinical Aspects of Hemoglobin Abnormalities*; Caughey, W. S., Ed.; Academic Press: New York, 1978; p 607.
(6) Tsubaki, M.; Yu, N.-T. *Proc. Natl. Acad. Sci. U.S.A.* **1981**, *78*, 3581.

(7) Mackin, H. C.; Tsukbaki, M.; Yu, N.-T. *Biophys. J.* **1983**, *41*, 349.

in "unprotected porphyrins" such as Co(TPP-d_8), marked enhancement of toluene modes occurs by Soret excitation when the $\nu(O_2)$ is shifted close to the toluene band by chooosing a proper base ligand. We noted, however, that this vibrational energy transfer does not occur in "completely protected porphyrins" such as Co(α^4-T$_{piv}$PP) even if the frequency matching condition is met. It is, therefore, of great interest to compare the degree of the bound O₂-toluene interaction in the α^4, α^3, cis-α^2, and trans-α^2 series.[9]

Second, we will examine the effect of changing the picket structure on the hydrogen bonding between bound O₂ and the o-acetamido NH group of the picket which has been proposed by several workers.[10-13] It is of our particular interest to obtain spectroscopic evidence for such interaction and to study the effect of changing the picket structure on it. A series of α^4-type Co picket fence porphyrins containing six different R groups[9] have been prepared for this purpose.

Finally, we will explore the possibility of hydrogen bonding between bound O₂ and the protic R group of the T$_{neo}$PP picket shown in Chart I. A series of seven $\alpha^3\alpha'$-type complexes in which α denotes the T$_{neo}$PP picket and α' represents a T$_{neo}$PP picket containing the OH or NH₂ group have been prepared for this purpose.[14,15] Model building studies suggested that such interactions would mimic the N—H(distal His)···O₂ hydrogen bonding found in MbO₂[16] and HbO₂[17] better than that of α^4-type picket fence porphyrins.

In the present work, we focused our attention on the $\nu(O_2)$ of these Co picket fence porphyrins since the $\nu(O_2)$ is well-recognized as a sensitive probe in detecting subtle changes in the O₂ environment.[8] Resonance enhancement of the $\nu(O_2)$ of analogous Fe complexes has not been successful except for those containing axial thiolate ligands.[18,19] This has been attributed to the small oscillator strength of the Fe–O₂ CT transition or to the unavailability of laser lines in the 780–1300-nm region where such transition is predicted.[20]

Experimental Section

Compounds. (*meso*-Tetrakis[α^4-o-(neopentylcarboxamido)phenyl]-porphyrinato)cobalt(II), Co(α^4-T$_{neo}$PP), and (*meso*-tetrakis[α^4-o-(pivalamido)phenyl]porphyrinato)cobalt(II), Co(α^4-T$_{piv}$PP), and their atropisomers were prepared by the method reported previously.[9] Deuteration of the o-acetamido protons of Co(α^4-T$_{neo}$PP) was made by dissolving it in CH₃OD and evaporating the solvent in vacuo. This process was repeated several times to ensure complete deuteriation. The four other α^4-type complexes containing aprotic R groups and seven $\alpha^3\alpha'$-type complexes in which α represents the T$_{neo}$PP picket and α' denotes a picket containing a protic R group (Table I) were also prepared as described previously.[14,15] The bases, 2-bromopyridine (2-BrPy), 3-acetylpyridine (3-AcPy), 3,5-dichloropyridine (3,5-ClPy), 4-phenylpyridine (4-PhPy), 1-methylimidazole (1-MeIm), 4-cyanopyridine (4-CNPy), and pyridine (Py), were purcharsed from Aldrich Chemical Co., Milwaukee, WI. These compounds were purified by distillation or recrystallization. The solvent, toluene, was distilled from metallic sodium. The gases, $^{16}O_2$ and $^{18}O_2$ (85%), were purchased from Airco and Monsanto Research Corp., respectively.

Spectral Measurements. The resonance Raman spectra were recorded on a Spex Model 1403 double monochromator equipped with a Spex
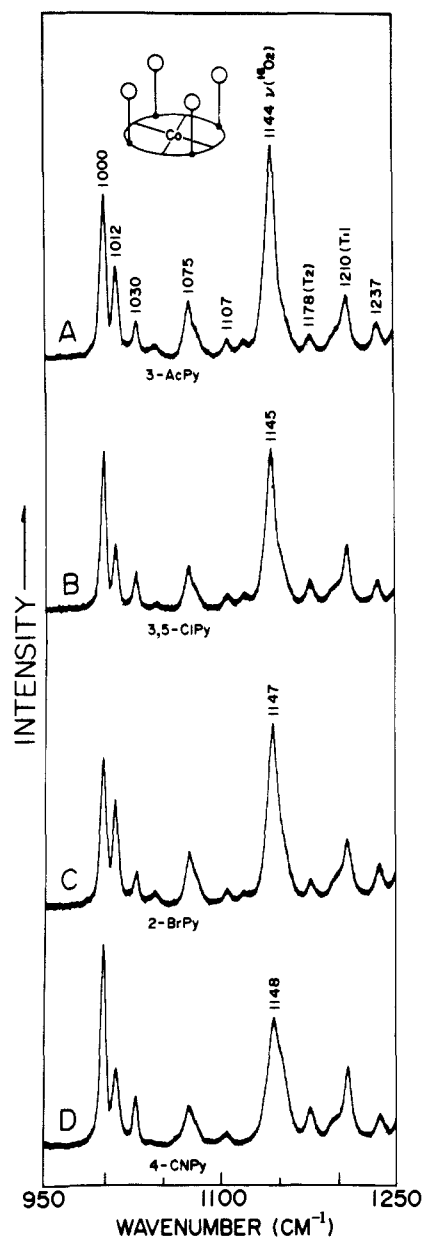
(8) Kincaid, J. R.; Proniewicz, L. M.; Bajdor, K.; Bruha, A.; Nakamoto, K. *J. Am. Chem. Soc.* **1985**, *107*, 6775.

(9) Imai, H.; Nakata, K.; Nakatsubo, A.; Nakagawa, S.; Uemori, Y.; Kyuno, E. *Synth. React. Inorg. Met.-Org. Chem.* **1983**, *13*, 761.

(10) Mispelter, J.; Momenteau, M.; Lavalette, D.; Lhoste, J.-M. *J. Am. Chem. Soc.* **1983**, *105*, 5165.

(11) Lavalette, D.; Tetreau, C.; Mispelter, J.; Momenteau, M.; Lhoste, J.-M. *Eur. J. Biochem.* **1984**, *145*, 555.

(12) Walker, F. A.; Bowen, J. *J. Am. Chem. Soc.* **1985**, *107*, 7632.

(13) Jameson, G. B.; Drago, R. S. *J. Am. Chem. Soc.* **1985**, *107*, 3017.

(14) Imai, H.; Nakatsubo, A.; Nakagawa, S.; Uemori, Y.; Kyuno, E. *Synth. React. Inorg. Met.-Org. Chem.* **1985**, *15*, 265.

(15) Imai, H.; Sekizawa, S.; Kyuno, E. *Inorg. Chim. Acta* **1986**, *125*, 151.

(16) Phillips, S. E. V.; Schoenborn, B. P. *Nature (London)* **1981**, *292*, 81.

(17) Shaanan, B. *Nature (London)* **1982**, *296*, 683.

(18) Chottard, G.; Schappacher, M.; Ricard, L.; Weiss, R. *Inorg. Chem.* **1984**, *23*, 4557.

(19) Bangcharoenpaurpong, O.; Rizos, A. K.; Champion, P. M.; Jollie, D.; Sligar, S. G. *J. Biol. Chem.* **1986**, *261*, 8089.

(20) Case, D. A.; Huynh, B. H.; Karplus, M. *J. Am. Chem. Soc.* **1979**, *101*, 4433.

Figure 1. RR spectra of Co(α^4-T$_{neo}$PP)(B)O₂ in toluene at ca. –90 °C (406.7 nm excitation). The axial base (B) is 3-acetylpyridine (trace A), 3,5-dichloropyridine (trace B), 2-bromopyridine (trace C), and 4-cyanopyridine (trace D).

DM1B controller. All the spectra were obtained by using 406.7-nm excitation from a Spectra-Physics Model 164-01 Kr-ion laser, except for those shown in Figure 6 which were obtained with the 441.6-nm line of a Liconix Model 4240 NB He–Cd laser. The minibulb techniques[21] were employed to measure the spectra of dioxygen adducts at ca. –90 °C. Proton NMR spectra were measured on a JEOL JMN-MH-100 spectrometer.

Results and Discussion

Interaction of Bound Dioxygen with Solvent. Figure 1 shows the RR spectra of Co(α^4-T$_{neo}$PP)(B)O₂ in toluene at ca. –90 °C containing a series of axial base ligands (B). In each case, a single sharp peak was observed at 1144–1148 cm⁻¹, and this band was assigned to the $\nu(O_2)$ since it is shifted to ~1070 cm⁻¹ by $^{16}O_2$/$^{18}O_2$ substitution. In contrast, the Co(α^3-T$_{neo}$PP)(B)O₂ series obtained under similar conditions (Figure 2) exhibits a shoulder band at 1154 cm⁻¹ and its intensity increases as the base ligand is changed in the order 3-AcPy, 3,5-ClPy, 2-BrPy, and 4-CNPy. Toluene exhibits three Raman bands[22] at 1210 (T₁), 1178 (T₂), and 1155

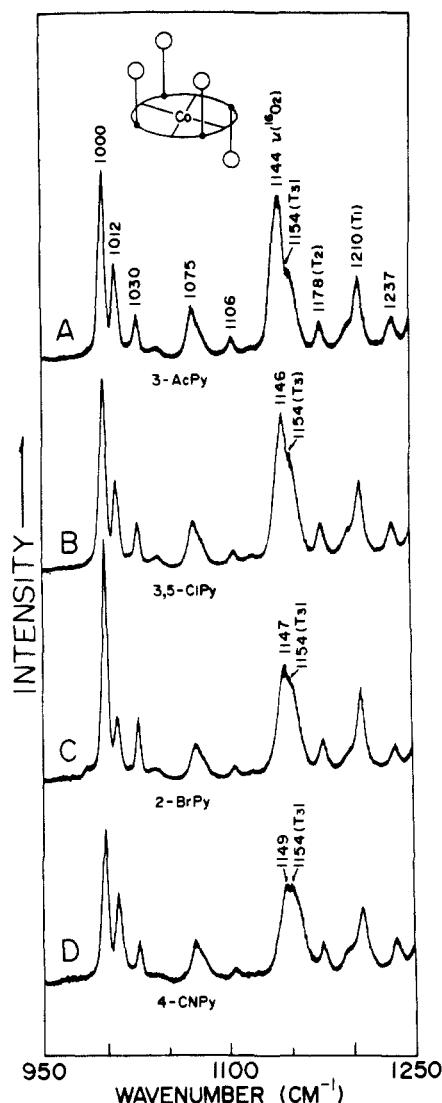(21) Bajdor, K.; Kincaid, J. R.; Nakamoto, K. *J. Am. Chem. Soc.* **1984**, *106*, 7741.

Figure 2. RR spectra of $Co(\alpha^3\text{-}T_{neo}PP)(B)O_2$ in toluene at ca. -90 °C (406.7 nm excitation). The axial base (B) is 3-acetylpyridine (trace A), 3,5-dichloropyridine (trace B), 2-bromopyridine (trace C), and 4-cyanopyridine (trace D).

Figure 3. RR spectra of $Co(\alpha^4\text{-}T_{piv}PP)(4\text{-}CNPy)O_2$ and $Co(\alpha^3\text{-}T_{piv}PP)(4\text{-}CNPy)O_2$ in toluene at ca. -90 °C (406.7-nm excitation).

Chart II

cm⁻¹ (T₃) whose relative intensity ratio is ca. 6:1:1 under our experimental conditions.[8] Thus, the anomalous enhancement of the T₃ band observed for the $Co(\alpha^3\text{-}T_{neo}PP)(B)O_2$ series indicates direct association of the toluene molecule with the bound dioxygen through a partial opening in the cavity. As stated previously,[8] the second condition for the bound O₂–toluene vibrational energy transfer is the frequency matching. This is accomplished by changing the basicity of the axial ligand since the ν(O₂) becomes higher as the ligand becomes more acidic.[8] The RR spectrum of $Co(\alpha^3\text{-}T_{neo}PP)(1\text{-}MeIm)O_2$ (pK_a 7.20) in toluene consists of two separated bands at 1141 (ν(O₂)) and 1154 cm⁻¹ (T₃) since these two bands are far apart (not shown in Figure 2). As the base ligand becomes more acidic, the ν(O₂) is shifted closer to the T₃ band and the latter band becomes stronger. This is clearly seen in Figure 2 where the base ligand is changed in the order 3-AcPy (3.18), 3,5-ClPy (3.4), 2-BrPy (0.90), and 4-CNPy (1.90). Although the numbers in the brackets indicate the pK_a values in aqueous solution,[23] their order does not change appreciably in nonaqueous solvents.[24] A small base ligand effect on the ν(O₂) is seen in the α⁴ series (Figure 1). However, the enhancement of the T₃ band does not occur in this case. The two structures
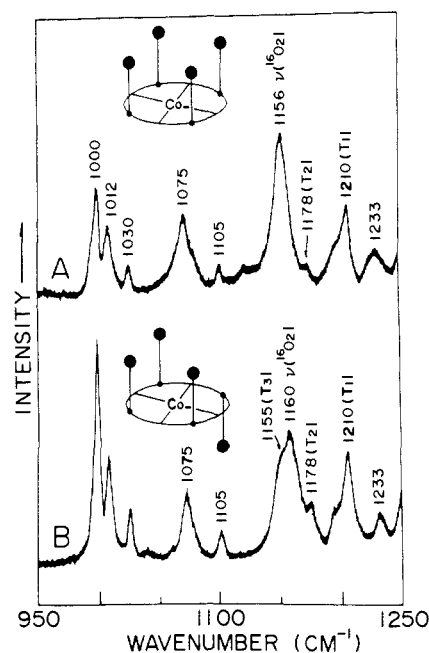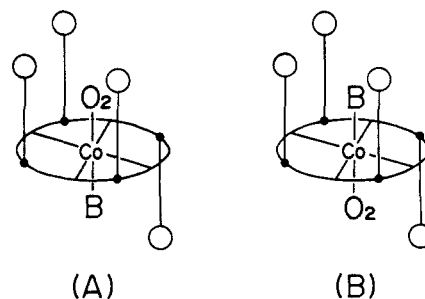
shown in Chart II are probable for the dioxygen adduct of a α³-porphyrin. However, structure B is less likely since a bulkier base ligand (relative to O₂) would occupy the axial position having less steric hindrance. The doublet feature of the ν(O₂) band shown in Figure 2 cannot be attributed to an equilibrium mixture of these two isomers, since the RR spectrum of the corresponding ¹⁸O₂ analogue exhibits a single peak near 1070 cm⁻¹.

Figure 3 compares the RR spectra of $Co(\alpha^4\text{-}T_{piv}PP)(B)O_2$ and $Co(\alpha^3\text{-}T_{piv}PP)(B)O_2$ in the toluene at ca. -90 °C where B is 4-CNPy. It is noted that the ν(O₂) of the former (1156 cm⁻¹) is 8 cm⁻¹ higher than that of $Co(\alpha^4\text{-}T_{neo}PP)(4\text{-}CNPy)O_2$ (1148 cm⁻¹, Figure 1D). Similarly, the ν(O₂) of $Co(\alpha^3\text{-}T_{piv}PP)(4\text{-}CNPy)O_2$ (1160 cm⁻¹) is 11 cm⁻¹ higher than that of $Co(\alpha^3\text{-}T_{neo}PP)(4\text{-}CNPy)O_2$ (1149 cm⁻¹, Figure 2D). Thus, the frequency order, ν(O₂) < ν(T₃), observed for the $T_{neo}PP$ is reversed in the $T_{piv}PP$ although the T₃ band is enhanced in both α³-porphyrins. The origin of the observed shift of ν(O₂) in going from the $T_{piv}PP$ to $T_{neo}PP$ complex will be discussed in the subsequent section.

Traces A and B of Figure 4 show the RR spectra of Co(cis-$\alpha^2\text{-}T_{piv}PP)(Py)O_2$ and its 4-CNPy analogue in toluene at ca. -90 °C, respectively. In the cis structure, direct interaction between the bound O₂ and toluene is possible since there is no steric barrier to prevent such association. As stated earlier, the ν(O₂) is shifted to higher frequency as the axial base ligand becomes more acidic. In the case of Py (pK_a 5.25), the ν(O₂) is at 1150 cm⁻¹, and only the T₃ band at 1155 cm⁻¹ is enhanced (Figure 4A). However, a more acidic base such as 4-CNPy (pK_a 1.90) shifts the ν(O₂) to 1164 cm⁻¹ which is between ν(T₂) and ν(T₃). Thus, the T₂ as well as T₃ band is enhanced as seen in Figure 4B.

Figure 4C shows the RR spectrum of Co(trans-$\alpha^2\text{-}T_{piv}PP)(4\text{-}CNPy)O_2$ in toluene at ca. -90 °C. The ν(O₂) appears as a weak shoulder near the T₃ band although its exact frequency cannot

(22) La Lau, C.; Synder, R. G. *Spectrochim. Acta* **1971**, *27A*, 2073.

(23) Perrin, D. D. *Dissociation Constants of Organic Bases in Aqueous Solution*; Butterworths: London, 1965.

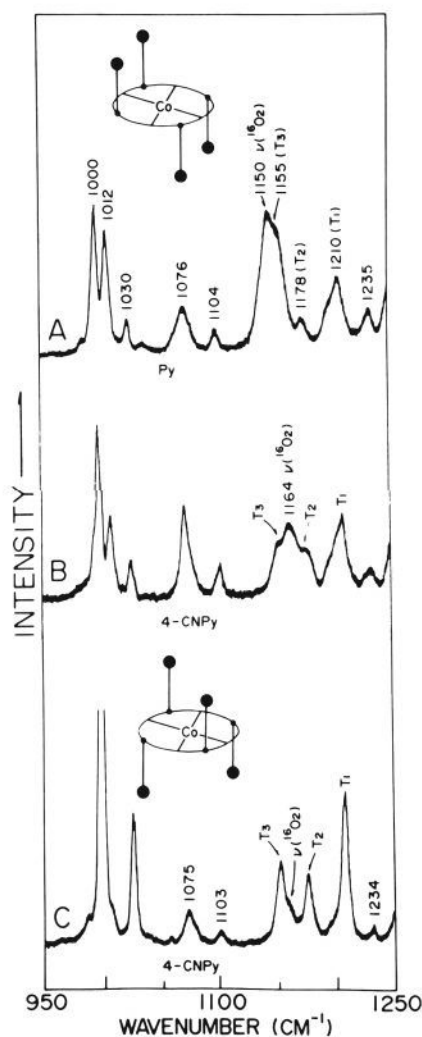(24) Bordwell, F. G.; Hughes, D. L. *J. Org. Chem.* **1982**, *47*, 3224.

RR Spectra of O_2 Adducts of Co Picket Fence Porphyrins

J. Am. Chem. Soc., Vol. 110, No. 3, 1988 745

Figure 4. RR spectra of Co(*cis*-α^2-T_{piv}PP)(py)O_2 (trace A), Co(*cis*-α^2-T_{piv}PP)(4-CNPy)O_2 (trace B), and Co(*trans*-α^2-T_{piv}PP)(4-CNPy)O_2 in toluene at ca. −90 °C (406.7-nm excitation).
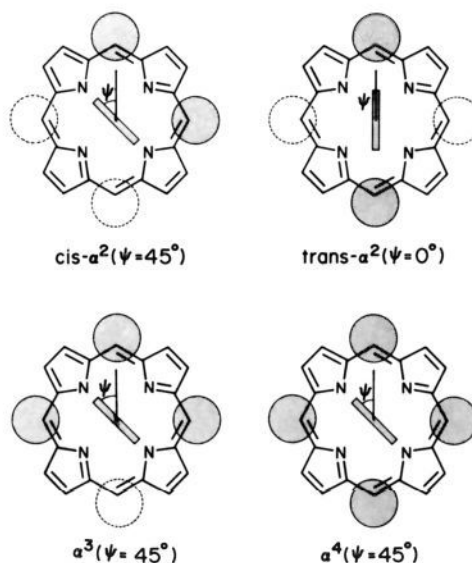

Figure 5. Schematic representations of relative positions of picket fence (cross-dotted and open circles, above and below the porphyrin core plane, respectively), base ligand plane (dotted rectangular boxes, below the porphyrin core plane), and Co–O–O plane (solid lines, above the porphyrin core plane).

be determined. The weakness of its $\nu(O_2)$ band may indicate a low concentration of the dioxygen adduct formed in the trans-α^2 isomer. As pointed out by Walker et al.,[25] the base ligand plane tends to take the eclipsed orientation in the cis and the staggered orientation in the trans complex relative to the N_p–Co–N_p (N_p: pyrrole nitrogen) axis of the porphyrin (Figure 5). According to Scheidt and Chipman,[26] the base ligand prefers to take the eclipsed orientation with respect to the N_p–Co–N_p axis in "unprotected" porphyrins. Walker et al.[25] demonstrated, however, that the base ligand is forced to take the staggered orientation in the trans-α^2 picket fence porphyrins due to steric repulsion from the *o*-pivalamido groups (Figure 5). On the other hand, the orientation of the Co–O–O plane is dictated by the direction of the N—H···O_2 hydrogen bond formed between the dioxygen and the *o*-acetamido N–H group (vide infra). Thus, more π-electron donation from the base to the dioxygen would occur via the Co–porphyrin in the cis than in the trans complex. This, in turn, would produce more O_2 adducts in the cis than in the trans complex. In the α^4 and α^3 atropisomers, the base ligand plane can take the eclipsed orientation with respect to the N_p–Co–N_p plane, and the resulting dihedral angle (ψ) between the base plane and the Co–O–O plane is similar to that of the cis-α^2 complex (45°). Although this angle is zero for the trans-α^2 complex, the staggered orientation of the base plane as well as the Co–O–O plane with

respect to the N_p–Co–N_p direction prevents electron flow from the base ligand to dioxygen.

It is interesting to note that as the oxygen affinity decreases, the $\nu(O_2)$ is shifted to higher frequency in the series of atropisomers of Co(T_{piv}PP)(B)O_2:

	α^4		α^3		cis-α^2
$P_{1/2}(O_2)$, Torr (15 °C) (B = 1-MeIm)[9]	80	<	570	<	1900
$\nu(O_2)$, cm^{-1} (B = 4-CNPy)	1156	<	1160	<	1164

Although the oxygen affinity is governed by several factors,[27] changes in the picket fence structure are largely responsible for the above order of $P_{1/2}(O_2)$. In the most protected α^4 complex, the bound O_2 is hydrogen bonded to the *o*-acetamido group of the picket (vide infra) and its $\nu(O_2)$ is the lowest in the series. However, this hydrogen bonding would be weakened and its $\nu(O_2)$ shifted to higher frequency when the solvent (toluene) molecule intrudes in the proximity of the bound O_2 in the "semiprotected" complexes. Thus, the above order of the $\nu(O_2)$ may be taken as a measure of the degree of such intrusion by the solvent molecule.

Figure 4 also indicates that the trans-α^2 complex exhibits two bands whereas the cis-α^2 complex exhibits three bands in the 1050–950-cm^{-1} region. The bands at 1030 and 1000 cm^{-1} are due to the solvent (toluene). However, the band at 1012 cm^{-1} appears in the cis but not in the trans complex. This provides a convenient means of distinguishing these two atropisomers since their electronic spectra (λ_{max}) are similar (530 and 414 nm for trans isomer and 527 and 412 nm for cis isomer).

Hydrogen Bonding between Bound Dioxygen and the *o*-Acetamido Group. The existence of hydrogen bonding between bound O_2 and the distal histidine of MbO$_2$ was first demonstrated by a neutron diffraction study that yielded the N—H···O_2 distance of 2.97 Å.[16] This was followed by X-ray analysis of HbO$_2$ that gave the N—H···O_2 distances of 2.7 and 3.2–3.4 Å for the α and β subunits, respectively.[17] Kitagawa et al.[28] noted that the $\nu(O_2)$ near 1134 cm^{-1} of CoMbO$_2$ and CoHbO$_2$ and its hybrid analogues are shifted by 2–5 cm^{-1} to higher frequencies when the solvent is changed from H$_2$O to D$_2$O. These observations not only confirmed the presence of such hydrogen bonding in the native
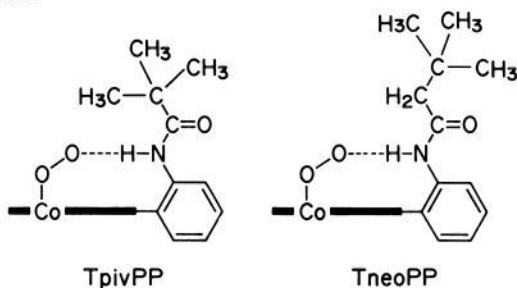
(25) Walker, F. A.; Buehler, J.; West, J. T.; Hinds, J. L. *J. Am. Chem. Soc.* **1983**, *105*, 6923.

(26) Scheidt, W. R.; Chipman, D. M. *J. Am. Chem. Soc.* **1986**, *108*, 1163.

(27) Collman, J. P.; Brauman, J. I.; Iverson, B. L.; Sessler, J. L.; Morris, R. M.; Gibson, Q. H. *J. Am. Chem. Soc.* **1983**, *105*, 3052.

(28) Kitagawa, T.; Ondrias, M. R.; Rousseau, D. L.; Ikeda-Saito, M.; Yonetani, T. *Nature (London)* **1982**, *298*, 869.

Chart III

TpivPP   TneoPP

proteins but also rendered support for the original assignments of the $\nu(O_2)$ by Tsubaki and Yu.[6]

As stated earlier, several groups of workers[10-13] proposed the presence of weak hydrogen bonding between bound O_2 and the o-acetamido NH group of the picket in $Fe(T_{piv}PP)(B)O_2$ and related compounds. Jameson and Drago[13] estimate this $N \cdots O_2$ distance to be ~ 4 Å which is much longer than those found in MbO_2 and HbO_2. According to these workers, one of the major factors in weakening the hydrogen bonding in $Fe(T_{piv}PP)(B)O_2$ is a relatively large repulsive force between the $C(CH_3)_3$ group and the bound dioxygen. As seen in Chart III, the $C(CH_3)_3$ group of $Co(\alpha^4-T_{neo}PP)(B)O_2$ is located further from the dioxygen and points outward from the picket fence. This would decrease the repulsion between them and shorten the $N-H \cdots O_2$ distance in the $T_{neo}PP$ complex. As a result, the $\nu(O_2)$ is shifted from 1156 to 1148 cm^{-1} in going from $Co(\alpha^4 T_{piv}PP)(B)O_2$ to $Co(\alpha^4-T_{neo}PP)(B)O_2$ (B = 4-CNPy). The amido NH signals of $H_2-(\alpha^4-T_{neo}PP)$ and $H_2(\alpha^4-T_{piv}PP)$ in $CDCl_3$ at 25 °C are observed at 6.99 and 7.20 ppm (δ scale), respectively. However, the order of their chemical shifts is opposite to what one expects from their acidity since the former proton is more acidic than the latter. This trend may be explained in terms of the π-current shielding effect of the porphyrin ring which is stronger in the former because its proton is located closer to the porphyrin ring relative to that of the latter.

In order to find out whether the $\nu(O_2)$ of these porphyrins are shifted by the NH/ND substitution of the o-acetamido groups, we have prepared the deuteriated analogue of $Co(\alpha^4-T_{neo}PP)$, namely $Co(\alpha^4-T_{neo}PP-d_4)$. Complete deuteration of the NH protons was confirmed by the disappearance of the weak band at 1259 cm^{-1} and the emergence of a new band at 1244 cm^{-1} in RR spectra. These bands are assigned to the amide III vibration that appears at 1298 cm^{-1} in N-methylacetamide and contains 30% N–H bending character.[29] As will be shown later (Figure 6), the band at 361 cm^{-1} also disappears by the deuteration.

The RR spectra of $Co(\alpha^4-T_{neo}PP)(4-PhPy)O_2$ and its $^{18}O_2$ analogue exhibit the $\nu(O_2)$ at 1147 and 1086 cm^{-1}, respectively (toluene-d_8, ca. −90 °C, 441.6 nm). However, these bands showed no appreciable shifts by deuteration of the NH protons. As stated earlier, the shift of $\nu(O_2)$ by NH/ND substitution is only 2–5 cm^{-1} for MbO_2 and HbO_2 (α subunit), which contain much stronger and shorter hydrogen bonds.[28] Although it is difficult to estimate the $NH \cdots O_2$ distance in $Co(\alpha^4-T_{neo}PP)(B)O_2$, the above result suggests that the $N-H \cdots O_2$ distances in these compounds are still too long to observe a discernible $\nu(O_2)$ shift by NH deuteration.

Traces A and B of Figure 6 show the RR spectra of $Co(\alpha^4-T_{neo}PP)(4-PhPy)O_2$ and its $^{18}O_2$ analogue below 550 cm^{-1}. It is seen that three bands at 520, 463, and 267 cm^{-1} are shifted to 508, 460, and 258 cm^{-1}, respectively, by $^{16}O_2/^{18}O_2$ substitution. The first band is assigned to the $\nu(Co-O_2)$ since a number of O_2 adducts of Co–porphyrins exhibit the $\nu(Co-O_2)$ in this region.[30] However, its oxygen isotope shift (12 cm^{-1}) is much smaller than those of other compounds (~ 21 cm^{-1}).[30] This result, combined with the small isotope shift (3 cm^{-1}) observed for the second band,
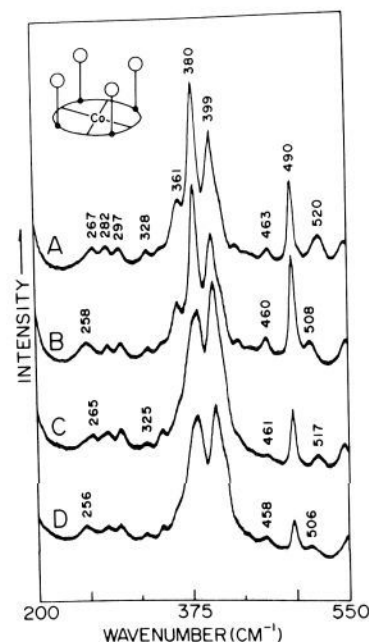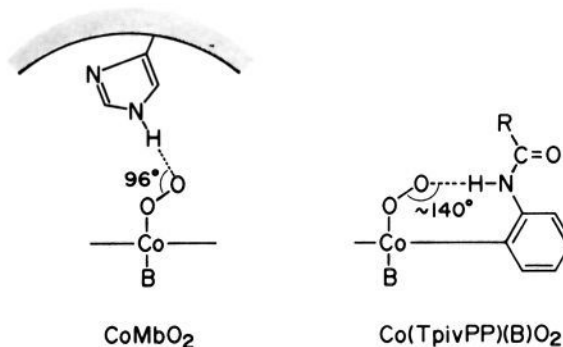

Figure 6. RR spectra of $Co(\alpha^4-T_{neo}PP)(4-PhPy)O_2$ (trace A, $^{16}O_2$ and trace B, $^{18}O_2$) and $Co(\alpha^4-T_{neo}PP-d_4)(4-PhPy)O_2$ (trace C, $^{16}O_2$ and trace D, $^{18}O_2$) in toluene-d_8 at ca. −90 °C (441.6-nm excitation).

Chart IV

CoMbO$_2$ Co(TpivPP)(B)O$_2$

suggests that there is strong vibrational coupling between these two modes. Although the nature of the second band is not known, it may involve the motion of the amido group since it is slightly sensitive to the NH/ND substitution (Figure 6, C and D). The last band at 267 cm^{-1} shows a large shift (9 cm^{-1}) by $^{16}O_2/^{18}O_2$ substitution. Previously, we[31] observed a similar isotope shift (8 cm^{-1}) for the 279-cm^{-1} band of $Fe(Pc)O_2$ (Pc = phthalocyanato ion) and assigned it to the $\delta(FeOO)$ (δ, bending) based on normal coordinate calculations. Hence, we assign the 267-cm^{-1} band of $Co(\alpha^4-T_{neo}PP)(4-PhPy)O_2$ to the $\delta(CoOO)$.

Figures 6, C and D, shows the RR spectra of $Co(\alpha^4-T_{neo}PP-d_4)(4-PhPy)O_2$ and its $^{18}O_2$ analogue. The three bands at 517, 461, and 265 cm^{-1} are shifted to 506, 458, and 256 cm^{-1}, respectively, by $^{16}O_2/^{18}O_2$ substitution. More importantly, all these vibrations are shifted 2–3 cm^{-1} to lower frequencies by the NH/ND substitution. These results provide definitive evidence for the presence of the $N-H \cdots O_2$ hydrogen bond in $Co(\alpha^4-T_{neo}PP)(4-PhPy)O_2$. Previously, Kitagawa et al.[28] noted that the $\nu(O_2)$ is sensitive while the $\nu(Co-O_2)$ (538 cm^{-1}) is not sensitive to NH/ND (distal His) substitution in CoMbO$_2$. As illustrated in Chart IV, the $N-H \cdots O-O$ geometry is markedly different between MbO_2 and $Co(T_{piv}PP)(B)O_2$; the N–H bond is almost

(29) Miyazawa, T.; Shimanouchi, T.; Mizushima, S. *J. Chem. Phys.* **1958**, *29*, 611.

(30) Bajdor, K.; Nakamoto, K.; Kincaid, J. *J. Am. Chem. Soc.* **1983**, *105*, 678.

(31) Bajdor, K.; Oshio, H.; Nakamoto, K. *J. Am. Chem. Soc.* **1984**, *106*, 7273.

(32) Spilburg, C. A.; Hoffman, B. M.; Petering, D. H. *J. Biol. Chem.* **1972**, *247*, 4219.

RR Spectra of O₂ Adducts of Co Picket Fence Porphyrins

J. Am. Chem. Soc., Vol. 110, No. 3, 1988 747

Table I. Thermodynamic Data for Oxygenation and Structural Data for Dioxygen Adducts

compd	$P_{1/2}(O_2)$, Torr	$\Delta G°$, kJ/mol	$\Delta H°$, kJ/mol	$\Delta S°$, J/(K·mol)	$\nu(O_2)$, cm⁻¹	$\nu(Co-O_2)$, cm⁻¹	N–H···O₂, Å
CoMb[a,32]	57	−6.42	−55.6	−165	~1122[6]	539[6]	2.97[16]
Co(α⁴-T_{neo}PP)[b,9]	120	−4.58	−55.2	−170	1137	520	3–4
Co(α⁴-T_{piv}PP)[b,9]	170	−3.71	−54.4	−170	1148	516[c,7]	~4[13]

[a] Data obtained in aqueous solution at 25 °C. [b] Data obtained in toluene solution at 25 °C. The axial ligand is 1-MeIm. [c] In benzene.
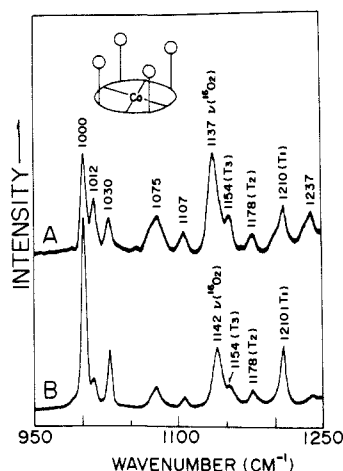
Figure 7. RR spectra of Co(α⁴-T_{neo}PP)(1-MeIm)O₂ in toluene at ca. −90 °C (trace A) and room temperature (trace B) (406.7-nm excitation).

perpendicular to the O–O bond in the former whereas this angle is about 140° in the latter. This difference in geometry between the native protein and its model compound may be responsible for the observed different behaviors of the $\nu(O_2)$ and $\nu(Co-O_2)$ upon NH/ND substitution.

Figure 7 compares the RR spectra of Co(α⁴-T_{neo}PP)(1-MeIm)O₂ at ca. −90 °C (trace A) and room temperature (trace B). The $\nu(O_2)$ of the former is at 1137 cm⁻¹, which is much lower than that of the analogous 3-AcPy derivative (1144 cm⁻¹, Figure 1A) measured under similar conditions since 1-MeIm (pK_a 7.20) is much more basic than 3-AcPy (pK_a 3.18). When this solution is warmed to room temperature, the $\nu(O_2)$ is shifted to 1142 cm⁻¹ although its intensity is decreased appreciably due to partial decomposition of the O₂ adduct. A shift of a similar magnitude is observed for the corresponding ¹⁸O₂ adduct by raising the temperature from ca. −90 °C (1065 cm⁻¹) to room temperature (1070 cm⁻¹). These results can be interpreted as an indication that the relatively strong N—H···O₂ bond at ca. −90 °C is weakened considerably at room temperature as a result of increasing thermal motion of the picket fence.

Table I lists thermodynamic data of oxygenation reactions, vibrational frequencies, and N—H···O₂ distances of the resulting dioxygen adducts. It is seen that, as the oxygen affinity increases, the $\nu(O_2)$ and $\nu(Co-O_2)$ bands shift to lower and higher frequencies, respectively, and the N—H···O₂ distance becomes shorter. Theoretically, the $\Delta H°$ values should be correlated to these spectroscopic and structural parameters. In fact, Table I shows that there is a similar relationship among these quantities. Yet, a quantitative discussion between thermodynamic and spectral data must be made with caution since these data were obtained in different solvents. Finally, it should be noted that in the case of CoMbO₂, the polar nature of the heme cavity[33] plays an important role in strengthening the N—H···O₂ bond and lowering the $\nu(O_2)$.

Modified α⁴- and α³α′-Type Picket Fence Porphyrins. Thus far, we have studied the effect of N—H···O₂ hydrogen bonding on the $\nu(O_2)$ of the two α⁴-type picket fence porphyrins, T_{neo}PP and T_{piv}PP. To investigate such effect further we have measured the RR spectra of O₂ adducts of eleven modified picket fence porphyrins of the α⁴- and α³α′-types. In the latter type, α denotes

(33) Traylor, T. G.; Koga, N.; Deardurff, L. A. *J. Am. Chem. Soc.* **1985**, *107*, 6504.

Table II. $\nu(O_2)$ of α⁴- and α³,α′-Type Picket Fence Porphyrins

R	abbreviation	$\nu(O_2)$,[a] cm⁻¹
α⁴-type		
–C(CH₃)₃	Co(T_{piv}PP)	1148
–CF₂CF₂CF₃	Co(T_{F·pro}PP)	1142
–CH(CH₃)₂	Co(T_{isopro}PP)	1142
–CH₂— (cyclohexylmethyl)	Co(T_{cych·m}PP)	1141
(cyclohexyl)	Co(T_{cych}PP)	1140
–CH₂–C(CH₃)₃	Co(T_{neo}PP)	1137
α³,α′-type		
(3,5-dimethylphenyl, CH₃/CH₃)	Co(tNDMP)	1146
(OCH₃/OCH₃)	Co(tNmBP)	1146
–CH₂OH	Co(tNHP)	1143
(NH₂/NH₂)	Co(tNDAP)	1140
–CH₂CH₂CONH₂	Co(tNC₄AP)	1139
–CH₂CONH₂	Co(tNC₃AP)	1139
(OH phenyl)	Co(tNHPP)	1139

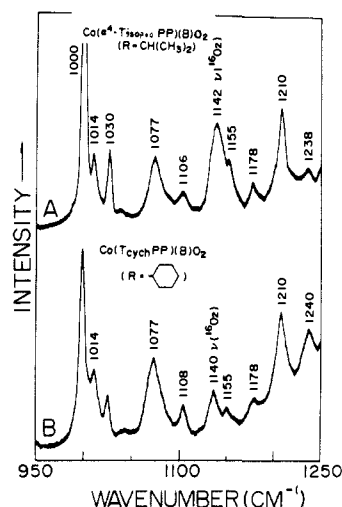[a] Obtained at ca. −90 °C in toluene with 1-MeIm as the base ligand.

Figure 8. RR spectra of Co(α⁴-T_{isopro}PP)(1-MeIm)O₂ (trace A) and Co(α⁴-T_{cych}PP)(1-MeIm)O₂ (trace B) in toluene at ca. −90 °C (406.7-nm excitation).

the T_{neo}PP picket while α′ represents a series of new pickets containing the R groups listed in Table II. In the α⁴ series, the $\nu(O_2)$ of the four new complexes are between those of Co(α⁴-T_{piv}PP) and Co(α⁴-T_{neo}PP) obtained under the same condition. Figure 8 shows the RR spectra of two representative compounds.
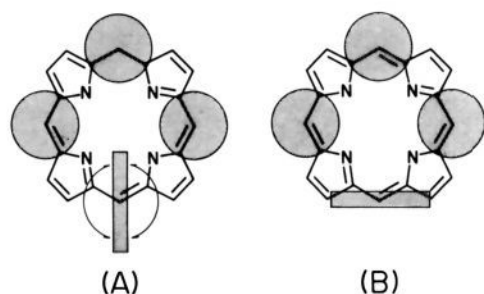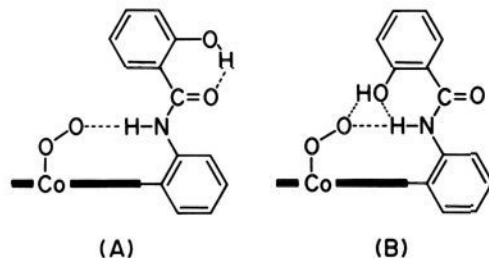
Figure 9. Schematic representation of two probable orientations of the α' picket (dotted rectangular box) relative to the α^3 pickets (cross-dotted circles) in $\alpha^3\alpha'$-type complexes.

Chart V

As discussed in the preceding section, the $\nu(O_2)$ of these complexes is determined by the degree of the steric repulsion among the pickets which, in turn, affects the strength of the N—H(o-acetamido)$\cdots O_2$ bond. Thus, the present result is interpreted as indicating that the steric repulsion in these new complexes is intermediate between those of Co(α^4-T$_{piv}$PP) and Co(α^4-T$_{neo}$PP). It is interesting to note that the polarity of the R group has no appreciably effect on the $\nu(O_2)$ as the $\nu(O_2)$ of Co(α^4-T$_{F-pro}$PP) is the same as that of Co(α^4-T$_{isopro}$PP).

As discussed earlier, the N—H$\cdots$O—O geometry of picket fence porphyrins such as T$_{piv}$PP is markedly different from those found MbO$_2$ and HbO$_2$. To mimic the native heme proteins more closely, Imai et al.[14] prepared a series of $\alpha^3\alpha'$-type complexes containing protic R groups listed in Table II. Those containing aprotic R groups of similar structures were also included for comparison. It is seen that the $\nu(O_2)$ of the first two compounds which contain no protic groups (1146 cm^{-1}) are close to that of Co(α^4-T$_{piv}$PP) (1148 cm^{-1}). The remaining five compounds contain protic R groups in the α' picket, and their $\nu(O_2)$ are at 1140–1139 cm^{-1} except for Co(tNHP) which exhibits the $\nu(O_2)$ at 1143 cm^{-1}. Thus, it appears that the presence of a protic R group lowers the $\nu(O_2)$ via hydrogen bonding to the bound O_2. A more rigorous comparison may be made for a series of $\alpha^3\alpha'$-type complexes in which α' pickets contain substituted phenyl groups of similar size. An NMR study on these compounds[15] shows that all these phenyl groups take the orientation A rather than B shown in Figure 9. Then, the steric repulsion among the pickets must be similar for these compounds. Yet, we observe a distinct shift
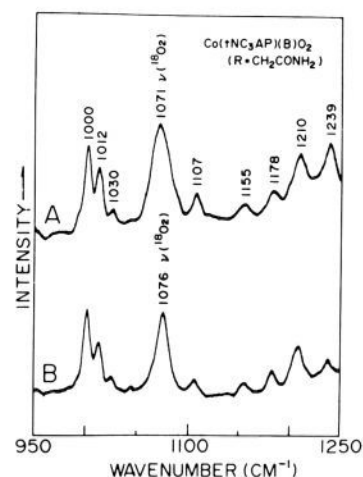

Figure 10. RR spectra of Co(tNC$_3$AP)(1-MeIm)O$_2$ in toluene at ca. −90 °C (trace A) and room temperature (trace B) (406.7-nm excitation).

of the $\nu(O_2)$ in going from Co(tNDMP) (1146) cm^{-1} to Co-(tNDAP) (1140 cm^{-1}).

Model building studies show that two types of hydrogen-bonding schemes such as shown in Chart V are probable for the O_2 adduct containing a protic R group in the α' picket shown in Figure 9A. The presence of the intramolecular hydrogen bonding such as shown in Chart VA was confirmed by the phenolic proton signal of H$_2$(tNHPP) which was observed at 11.5 ppm in pyridine-d_5 at room temperature.[14] It was not possible, however, to distinguish structures VA and VB either by NMR or Raman spectroscopy. Figure 10 shows the temperature dependence of the RR spectrum of Co(tNC$_3$AP)(1-MeIm)($^{18}O_2$); the $\nu(^{18}O_2)$ is shifted from 1071 to 1076 cm^{-1} by raising the temperature from ca. −90 °C to room temperature. (The relatively weak porphyrin band at 1077 cm^{-1} (see Figure 8) is hidden under the $\nu(^{18}O_2)$ band). We assign the $\nu(^{18}O_2)$ at 1071 cm^{-1} to the O_2 adduct shown either by VA or VB. At room temperature, this band is shifted to 1076 cm^{-1} due to the weakening of the hydrogen bonding by thermal motion of the pickets. It should be noted, however, that the $\nu(^{16}O_2)$ of Co-(tNC$_3$AP)(1-MeIm)O$_2$ (1139 cm^{-1}) is still higher than that of Co(α^4-T$_{neo}$PP)(1-MeIm)O$_2$ (1137 cm^{-1}) at ca. −90 °C. Thus, the introduction of a protic R group in the picket does not necessarily lead to the bound O_2 which is more stable than that found in the latter compound. In fact, the $P_{1/2}(O_2)$ values of these complexes (Torr, 25 °C) are reported to be 1600 and 120, respectively.[14]