A Quantum Chemical Survey of Metalloporphyrin−Nitrosyl Linkage Isomers: Insights into the Observation of Multiple FeNO Conformations in a Recent Crystallographic Determination of Nitrophorin 4

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Abstract: Using density functional theory-based geometry optimizations, we have searched for η^1-NO, η^1-ON (isonitrosyl), and η^2-NO (side-on bound NO) linkage isomers of a number of metalloporphyrin−NO complexes, M(Por)(NO)(L), where Por = porphinato dianion, M = Mn(II), Fe(II), Fe(III), Ru(II), Ru(III), Co(II), and Rh(II), and L = no ligand, SMe, Ph, and imidazole. The η^1-NO isomer had the lowest energy in all cases, and the isonitrosyl isomer was also located as a higher energy potential energy minimum in a number of cases. The η^2-NO isomer was only located as a minimum for Mn(II) (L = no ligand), Fe(III) (L = no ligand), and Ru(III) (L = Ph, imidazole, pyrdine), suggesting that an $\{MNO\}^6$ electron count is important for stabilization of the η^2 mode of ligation. However, in the presence of axial ligands L, the side-on isomers of $\{FeNO\}^6$ complexes were not stable and opened up to an unusual geometry where the FeN(O) and NO vectors were tilted in opposite directions relative to the heme normal. Exactly such a geometry, as well as a "normal" upright geometry, has been observed in a recent crystallographic determination of nitrophorin 4 (*Nature Struct. Biol.* **2000**, *7*, 551), a salivary protein from the blood-sucking insect *Rhodnius prolixus*. Together, the calculated and experimental result illustrate the extreme softness of the FeNO potential energy surface toward various forms of tilting and bending deformations.

For many years, the interaction of diatomic molecules such as CO, NO, and O_2 with heme proteins has served as the paradigm of protein−ligand interactions.[1] A key question in this area and one that has attracted considerable attention in recent years involves how respiratory proteins such as myoglobin (Mb) and hemoglobin (Hb) discriminate between O_2 and CO.[2] On the basis of early X-ray and neutron diffraction studies on MbCO, which revealed highly bent FeCO angles of 120−140°, Collman suggested that the discrimination stems from protein steric interactions which force the bound CO into an energetically unfavorable bent orientation, while for bound O_2, such a bent geometry is the natural, energetically preferred one.[3]

In 1994−1995, IR photoselection[4] and polarized IR[5] experiments provided strong evidence for an essentially upright FeCO unit in MbCO. In addition, the relatively high frequency of the FeCO bending modes of carbonmonoxyhemes of around 500 cm^{-1} suggested that the FeCO unit is too stiff to undergo significant bending.[6] Thus, in the mid-1990s, Collman's "bent-CO hypothesis" gave way to a picture of MbCO involving a relatively rigid, upright FeCO unit.[7]

In 1996, Ghosh and Bocian addressed this issue using density functional theory, presenting a potential energy surface, $V(\tau, \beta)$, for tilting (τ) and bending (β) deformations of the FeCO unit.[8] The key features of this potential, subsequently confirmed and refined by Spiro and co-workers,[9] included an unusually large, negative tilt−bend interaction constant $k_{\tau\beta}$. While ruling out extremely bent FeCO angles of 120−140°, the Ghosh−Bocian potential indicated that the FeCO unit was indeed significantly deformable, provided tiling and bending occurred in a cooperative, in-phase manner.[8] The low energies associated with deformation of the FeCO unit cannot account for more than a minor fraction of the energy associated with discrimination of O_2 vs CO by Mb. In the currently favored picture,[2,9] the key interactions underlying this discrimination appear to involve hydrogen bonding interactions between bound O_2 and the distal histidine residue, although Collman[1] emphasizes the multifaceted character of the problem and the possibility that multiple factors of comparable importance may affect the binding affinities of diatomic gases with heme proteins.

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(1) Collman, J. P.; Fu, L. *Acc. Chem. Res.* **1999**, *32*, 455.

(2) For a series of review articles on this topic by different authors, see: Ghosh, A., Ed. *J. Biol. Inorg. Chem.* **1997**, *2*, 515−552.

(3) Collman, J. P.; Brauman, J. I.; Halbert, T. R.; Suslick, K. S. *Proc. Natl. Acad. Sci. U.S.A.* **1976**, *73*, 3333.

(4) Lim, M.; Jackson, T. A.; Anfinrud, P. A. *Science* **1995**, *269*, 962.

(5) Ivanov, D.; Sage, J. T.; Keim, M.; Powell, J. R.; Asher, S. A.; Champion, P. M. *J. Am. Chem. Soc.* **1994**, *116*, 4139.

(6) Ray, G. B.; Li, X.-Y.; Ibers, J. A.; Sessler, J. L.; Spiro, T. G. *J. Am. Chem. Soc.* **1994**, *116*, 162.

(7) Service, R. F. *Science* **1995**, *269*, 921.

(8) Ghosh, A.; Bocian, D. F. *J. Phys. Chem.* **1996**, *100*, 6363.

(9) (a) Spiro, T. G.; Kozlowski, P. M. *J. Am. Chem. Soc.* **1998**, *120*, 4524. (b) Vogel, K. M.; Kozlowski, P. M.; Zgierski, M. Z.; Spiro, T. G. *J. Am. Chem. Soc.* **1999**, *121*, 9915. This paper describes DFT calculations on FeCO, FeNO, and FeO_2 adducts and, in particular, points out that DFT (or, at least, certain commonly used functionals) may not adequately descibe the *trans* effect of the NO ligand in heme−NO adducts. This issue will be explored further in the course of future studies.

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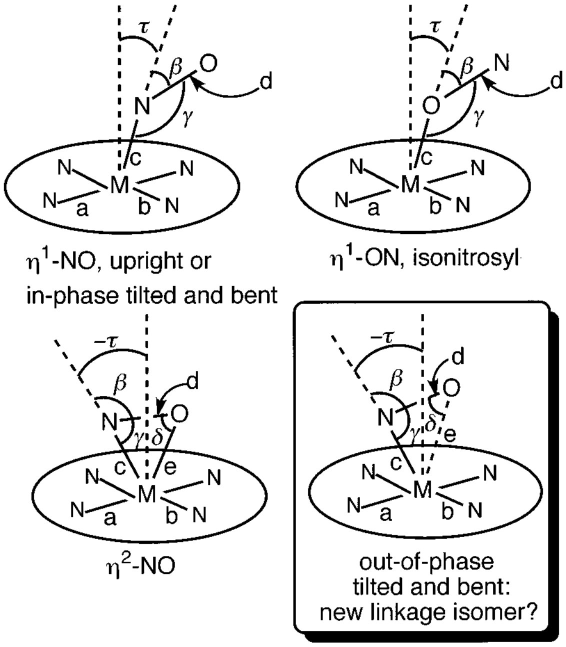
While a certain degree of closure appears to have been brought to our understanding of myoglobin's interaction with O_2 and CO, an explosion of new discoveries has taken place that impinge on the general area of heme−diatomic interactions. From a biological point of view, perhaps the most important development has been the emergence of the field of heme-based sensing. Examples of diatomic-sensing proteins that have adapted the heme unit for regulatory functions include the NO receptor guanylate cyclase,[10] the O_2 sensor FixL,[11] and the CO-sensing transcription activator CooA.[12] Another significant development has involved the recognition that interactions of iron(III) porphyrins and NO[13] are also of importance for a number of proteins and enzymes, including heme cd1 nitrite reductase,[14] cytochrome P450 nitric oxide reductase (P450NOR),[15] and the nitrophorins.[16]

The past few years have also seen key advances in our understanding of the fundamental physical and chemical properties of metalloporphyrin−NO complexes.[17] For example, the Ghosh−Bocian potential for metal(d^6)−CO complexes appears to apply to isoelectronic $\{MNO\}^6$ complexes as well (where we have used the commonly used Enemark−Feltham[18] notation for indicating electron counts), at least for moderate degrees of tilting and bending (say, $-20° < \tau, \beta < 20°$). Thus, X-ray crystallographic analyses of the $\{MNO\}^6$ complexes, $[Fe(OEP)(Ph)(NO)]^0$ and $[Ru(OEP)(SPh)(NO)]^0$, have revealed cooperatively tilted and bent MNO units with significant deviations of the NO vector from the heme normal.[19] An X-ray crystallographic analysis of P450NOR has also revealed significant cooperative tilting and bending of the $\{FeNO\}^6$ unit.[15] For each of these structures, the bend exceeds the tilt ($\beta > \tau$), a feature consistent with the Ghosh−Bocian potential.[8] Interestingly, metalloporphyrin−NO complexes also exhibit an entirely new aspect of flexibility not foreseen on the basis of this potential function, viz. the phenomenon of linkage isomerism. Thus, Bagley, Coppens, and Richter-Addo and co-workers have reported IR spectroscopic characterization of the isonitrosyl complexes $[Fe(OEP)(\eta^1\text{-ON})]^0$ and $[Fe(TTP)(\eta^1\text{-ON})]^0$, obtained as low-temperature photoproducts from the corresponding nitrosyl complexes.[20] Fomitchev and Richter-Addo have also presented IR spectroscopic evidence that low-temperature irradiation of $Ru^{III}(OEP)(NO)(L)$ produces the metastable η^1-ON and η^2-NO linkage isomers, where the axial ligand L can vary considerably.[21] Finally, an X-ray crystallographic analysis of nitrophorin 4, an NO-binding heme protein found in the saliva of the blood-sucking insect *Rhodnius prolixus*, revealed two distinct NO orientations including a normal relatively upright orientation and an unusual conformation in which the FeN(O) and NO vectors were each strongly tilted, but in opposite directions relative to the heme normal.[16c] The authors have proposed that the second orientation may correspond to "loosely bound" or side-on bound NO.[16c] The various possible MNO geometries observed or proposed for metalloporphyrin−NO linkage isomers are summarized in Scheme 1. In this study, we shall present a first quantum chemical survey of metalloporphyrin−nitrosyl linkage isomers and shall also propose a new explanation for the observation of two FeNO conformers for nitrophorin 4.[16c]

Scheme 1



The present investigation aims to address the following questions using density functional theory (DFT) calculations. (1) For which particular metalloporphyrins (i.e., which particular metals) are the η^1-ON and η^2-NO linkage isomers expected to be metastable species, i.e., local minima on the potential energy surface of the ground electronic state? In other words, how does the electron count n of $\{MNO\}^n$ porphyrin complexes determine the stability of the various NO linkage isomers? (2) What are the salient geometrical characteristics of the different linkage isomers? This proved to be an interesting issue, the key new result being that in certain cases the NO ligand may be described as intermediate between η^1- and η^2-NO. (3) Finally, what do

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[10] For representative recent publications on this topic, see the following articles and references therein: (a) Sharma, V. S.; Magde, D. *Methods − A Companion To Methods In Enzymology*; 1999; Vol. 19, p 494. (b) Zhao, Y.; Brandish, P. E.; Ballou, D. P.; Marletta, M. A. *Proc. Natl. Acad. Sci. U.S.A.* **1999**, *96*, 14753.

[11] (a) Rodgers, K. R.; Lukat-Rodgers, G. S.; Tang, L. *J. Biol. Inorg. Chem.* **2000**, *5*, 642. (b) Miyatake, H.; Mukai, M.; Park, S. Y.; Adachi, S.; Tamura, K.; Nakamura, H.; Nakamura, K.; Tsuchiya, T.; Iizuka, T.; Shiro, Y. *J. Mol. Biol.* **2000**, *301*, 415. (c) Gong, W. M.; Hao, B.; Chan, M. K. *Biochemistry* **2000**, *39*, 3955. (d) Rodgers, K. R.; Lukat-Rodgers, G. S.; Tang, L. *J. Am. Chem. Soc.* **1999**, *121*, 11241.

[12] (a) Uchida, T.; Ishikawa, H.; Ishimori, K.; Morishima, I.; Nakajima, H.; Aono, S.; Mizutani, Y.; Kitagawa, T. *Biochemistry* **2000**, *39*, 12747. (b) Chan, M. K. *Nature Struct. Biol.* **2000**, *7*, 822. (c) Lanzilotta, W. N.; Schuller, D. J.; Thorsteinsson, M. V.; Kerby, R. L.; Roberts, G. P.; Poulos, T. L. *Nature Struct. Biol.* **2000**, *7*, 876.

[13] Scheidt, W. R.; Ellison, M. K. *Acc. Chem. Res.* **1999**, *32*, 350.

[14] (a) Fulop, V.; Moir, J. W. B.; Ferguson, S. J.; Hajdu, J. *J. Mol. Biol.* **1993**, *232*, 1211. (b) Moir, J. W. B.; Baratta, D.; Richardson, D. J.; Ferguson, S. J. *Eur. J. Biochem.* **1993**, *212*, 377. (c) Weegaerssens, E.; Wu, W. S.; Ye, R. W.; Tiedje, J. M.; Chang, C. K. *J. Biol. Chem.* **1991**, *266*, 7496.

[15] (a) Shimizu, H.; Park, S. Y.; Lee, D. S.; Shoun, H.; Shiro, Y. *J. Inorg. Biochem.* **2000**, *81*, 191. (b) Shimizu, H.; Obayashi, E.; Gomi, Y.; Arakawa, H.; Park, S. Y.; Nakamura, H.; Adachi, S.; Shoun, H.; Shiro, Y. *J. Biol. Chem.* **2000**, *275*, 4816. (c) Obayashi, E.; Takahashi, S.; Shiro, Y. *J. Am. Chem. Soc.* **1998**, *120*, 12964.

[16] (a) Andersen, J. F.; Montfort, W. R. *J. Biol. Chem.* **2000**, *275*, 30496. (b) Schunemann, V.; Benda, R.; Trautwein, A. X.; Walker, F. A. *Israel, J. Chem.* **2000**, *40*, 9. (c) Weichsel, A.; Andersen, J. F.; Roberts, S. A.; Montfort, W. R. *Nature Struct. Biol.* **2000**, *7*, 551.

[17] (a) Westcott, B. L.; Enemark, J. H. In *Inorganic Electronic Structure And Spectroscopy*; Solomon, E. I., Lever, A. B. P., Eds.; Wiley-Interscience: New York, 1999; Vol. 2, Chapter 7, pp 403−450. (b) Cheng, L.; Richter-Addo, G. B. In *The Porphyrin Handbook*; Kadish, K. M., Smith, K. M., Guilard, R., Eds.; Academic: New York, 2000; Vol. 4, Chapter 33, pp 219−291.

[18] Enemark, J. H.; Feltham, R. D. *Coord. Chem. Rev.* **1974**, *13*, 339.

[19] (a) Fee, J. Y.; Yi, G. B.; Khan, M. A.; Richter-Addo, G. B. *Inorg. Chem.* **1999**, *38*, 4578. (b) Scheidt, W. R., personal communication.

[20] Cheng, L.; Novozhilova, I.; Kim, C.; Kovalevsky, A.; Bagley, K. A.; Coppens, P.; Richter-Addo, G. B. *J. Am. Chem. Soc.* **2000**, *122*, 7142.

[21] Fomitchev, D. V.; Coppens, P.; Li, T. S.; Bagley, K. A.; Chen, L.; Richter-Addo, G. B. *Chem. Commun.* **1999**, 2013.

Table 1. Energetics (eV) of Different Metalloporphyrin−NO Linkage Isomers[a,b]

	M(η^1-NO)			
formula	in-phase/upright	out-of-phase[c]	M(η^1-ON)	M(η^2-NO)
{MNO}^{6}				
Mn(P)(NO)	0.0000	NI	1.9016	1.6698
[Fe$^{\mathrm{III}}$(P)(NO)]$^+$	0.0000	NI	1.7505	1.4609
[Fe$^{\mathrm{III}}$(P)(NO)(Cl)]	0.0000	1.1998	NI	OU
[Fe$^{\mathrm{III}}$(P)(NO)(SCH_3)]	0.0000	1.0560	NI	OU
[Fe$^{\mathrm{III}}$(P)(NO)(Im)]$^+$	0.0000	1.3364	NI	OU
[Fe$^{\mathrm{III}}$(P)(NO)(Ph)]	0.0000	0.9049	NI	OU
[Ru$^{\mathrm{III}}$(P)(NO)]$^+$	0.0000	NI	2.0168	1.4989
[Ru$^{\mathrm{III}}$(P)(NO)(Cl)]	0.0000	NI	NI	1.2343
[Ru$^{\mathrm{III}}$(P)(NO)(SCH_3)]	0.0000	1.0756	NI	OU
[Ru$^{\mathrm{III}}$(P)(NO)(Im)]$^+$	0.0000	NI	NI	1.5453
[Ru$^{\mathrm{III}}$(P)(NO)(Ph)]	0.0000	0.8191	NI	OU
{MNO}^{7}				
Fe(P)(NO)	0.0000	−	1.5070	OU
Ru(P)(NO)	0.0000	−	1.3062	OU
{MNO}^{8}				
Co(P)(NO)	0.0000	−	1.1980	OU
Rh(P)(NO)	0.0000	−	1.6708	OU

[a] OU = opened up. [b] NI = not investigated. [c] The out-of-phase tilted and bent forms were not specifically searched for. They are reported only when approximate M(η^2-NO) starting geometries partially opened up to the out-of-phase tilted and bent forms.

the two different NO orientations in the X-ray crystallographic determination of nitrophorin 4 signify?[16c]

DFT[22−25] calculations with Slater-type triple-ζ plus polarization basis sets and C_s symmetry-constrained geometry optimization were carried out on the following complexes: [M(P)(NO)]^0 (M = Mn, Fe, Ru, Co, Rh), [M(P)(NO)]$^+$ (M = Fe, Ru), [M(P)(NO)(imidazole)]$^+$ (M = Fe, Ru), and [M(P)(NO)(L)]^0 (M = Fe, Ru; L = Cl, Ph, SCH_3).[26] In general, geometry optimizations were attempted for the η^1-NO, η^1-ON, and η^2-NO linkage isomers. Table 1 presents the relative energetics of the different linkage isomers located as potential energy minima.

In general, the η^1-NO and η^1-ON linkage isomers could be optimized for the various molecules studied. In all cases, the ordinary η^1-NO isomer was the global minimum, with the η^1-ON isomer 1.06−1.47 eV higher, as shown in Table 1. The relative energies of the η^1-ON isomers are such that they can indeed be expected to be metastable at liquid-nitrogen or lower temperatures, but, on warming they are expected to isomerize to the η^1-NO isomers. Thus, the isonitrosyl complexes Fe(TPP)(η^1-ON) and Fe(OEP)(η^1-ON) have been generated as low-temperature photoproducts derived from the corresponding η^1-NO complexes and characterized by infrared spectroscopy.[19] The optimized geometrical parameters of these molecules, listed in Table S1 in the Supporting Information, are not of particular interest except that the optimized geometries of [M(P)(NO)(L)]^0 (M = Fe, Ru, L = SCH_3, Ph) exhibit significant in-phase tilting and bending, as observed in related crystallographically characterized structures.[19]

In contrast, *η^2-NO linkage isomers were obtained as optimized structures in only certain cases*, viz. Mn(P)(NO), [Fe(P)(NO)]$^+$ with no axial ligand, Ru(P)(NO)(Cl), and [Ru(P)(NO)(L)]$^+$ (L = no ligand, imidazole, and pyridine). Compared to the corresponding η^1-NO isomers, the η^2-NO isomers were higher in energy by 1.23 (for Ru(P)(NO)(Cl)) to 1.67 eV (for Mn(P)(NO)). Consistent with these results, the following metalloporphyrin η^2-NO complexes have been experimentally observed: Ru(OEP)(η^2-NO)(L), where L = O-*i*-C_5H_{11}, SCH_2CF_3, Cl) and [Ru(P)(NO)(pyridine)]$^+$.[21] These results suggest that *an {MNO}^{6} electron count is important for stabilization of the η^2-NO coordination mode*.[27,28] Fomitchev and Coppens have also reached the same conclusion empirically on the basis of a survey of light-induced metastable linkage isomers of *nonporphyrin* transition metal complexes.[29]

Table S2 in the Supporting Information lists important geometrical parameters of the various η^2-NO structures optimized. Two examples are mentioned here. [Fe(P)(NO)]$^+$: FeN(NO) 1.789 Å, FeO(NO) 2.182 Å, NO 1.196 Å, ∠FeNO 91.8°, ∠FeON 55.0°, and ∠NFeO 33.2°. [Ru(P)(NO)(pyridine)]$^+$: RuN(NO) 2.011 Å, RuO(NO) 2.357 Å, NO 1.182 Å, ∠RuNO 91.4°, ∠RuON 58.6°, and ∠NRuO 30.0°. In other

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(22) The calculations used the PW91 exchange-correlation functional, triple-ζ plus polarization Slater-type basis sets, a fine mesh for numerical integrations, and full geometry optimizations including tight criteria for atomic forces and displacements, as implemented in the ADF program system. The ADF program was obtained from: Scientific Computing and Modelling, Department of Theoretical Chemistry, Vrije Universiteit, 1081 HV Amsterdam, The Netherlands. The geometry optimizations used C_s symmetry constraints, with the MNO plane as the plane of symmetry. Both spin-restricted and spin-unrestricted calculations were carried out on all the open-shell (S = 1/2) molecules studied and, in each case, nearly identical final geometries were obtained.

(23) For reviews of DFT-based structural studies on porphyrins and metalloporphyrins, see: (a) Ghosh, A. In *The Porphyrin Handbook*; Kadish, K. M., Smith, K. M., Guilard, R., Eds.; Academic: New York, 2000; Vol. 7, Chapter 47, pp 1−38. (b) Ghosh, A. *Acc. Chem. Res.* **1998**, *31*, 189.

(24) For other DFT calculations on transition metal porphyrin complexes from our laboratory, see: (a) Ghosh, A.; Gonzalez, E.; Vangberg, T. *J. Phys. Chem. B* **1999**, *103*, 1363. (b) Vangberg, T.; Ghosh, A. *J. Am. Chem. Soc*. **1999**, *121*, 12154. (c) Ghosh, A.; Wondimagegn, T.; Gonzalez, E.; Halvorsen, I. *J. Inorg. Biochem*. **2000**, *78*, 79. (d) Ghosh, A.; Wondimagegn, T.; Parusel, A. B. J. P. *J. Am. Chem. Soc*. **2000**, *122*, 5100. (e) Ghosh, A.; Gonzalez, E. *Isr. J. Chem*. **2000**, *40*, 1. (f) Wondimagegn, T.; Ghosh, A. *J. Am. Chem. Soc*. **2000**, *122*, 6375−6381. (g) Wondimagegn, T.; Ghosh, A. *J. Phys. Chem. B* **2000**, *104*, 10858.

(25) For a theoretical study of NO tilting and equatorial asymmetry in metalloporphyrin−NO complexes, see: Ghosh, A.; Wondimagegn, T. *J. Am. Chem. Soc*. **2000**, *122*, 8101. This study is based on experimental observations described in: Scheidt, W. R.; Duval, H. F.; Neal, T. J.; Ellison, M. K. *J. Am. Chem. Soc*. **2000**, *122*, 4651.

(26) Because of potential ambiguities with regard to metal oxidation states in nitrosyl complexes, the molecular formulas used in this paper do not explicitly indicate the metal oxidation states. However, the overall charge of the molecule or ion in question is carefully indicated in each case.

(27) Relatively few {FeNO}^{6} porphyrin complexes are known and a good summary is given in: Ellison, M. K.; Scheidt, W. R. *J. Am. Chem. Soc*. **1999**, *121*, 5210.

(28) Metastable η^2-NO forms have also been obtained at low temperature for the nitroprusside ion, $[Fe(CN)_5(NO)]^{2-}$, an {MNO}^{6} species, and for CpNi(NO), an {MNO}^{10} species.[17a]

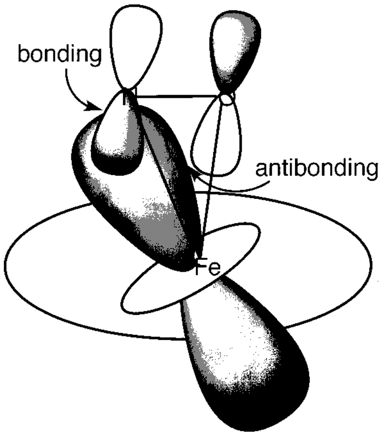
(29) (a) Fomitchev, D. V.; Novozhilova, I.; Coppens, P. *Tetrahedron* **2000**, *56*, 6813. (b) Fomitchev, D. V.; Coppens, P. *Comments Inorg. Chem*. **1999**, *21*, 131.

words, for the optimized η^2-NO structures, the MN(NO) distance is about 0.34−0.39 Å shorter than the MO(NO) distance.

Unlike Mn(P)(NO), $[Fe(P)(NO)]^+$ with no axial ligand, Ru(P)(NO)(Cl), and $[Ru(P)(NO)(L)]^+$ (L = no ligand, imidazole, and pyridine), attempted optimization of $[Fe(P)(\eta^2\text{-NO})(L)]^0$ (L = Cl, Ph, SCH_3), $[Fe(P)(\eta^2\text{-NO})(\text{imidazole})]^+$, and $[Ru(P)(\eta^2\text{-NO})(L)]^0$ (L = Ph, SCH_3) led to partially ring-opened MNO geometries in which the MN(O) and NO vectors are tilted in *opposite* directions relative to the heme normal. The optimized Fe−N(NO) and Fe−O(NO) distances in these out-of-phase tilted and bent (to use the phraseology of ref 8) FeNO complexes are 1.92−1.97 and 2.44−2.50 Å, respectively, which may be compared to analogous but significantly shorter distances of 1.79 and 2.18 Å for $[Fe(P)(\eta^2\text{-NO})]^+$, respectively.

These last results appear to be relevant to a recent high-resolution crystallographic determination of nitrophorin 4 where, in addition to a relatively upright FeNO conformer, another conformer was also seen where the NO ligand is closer to being parallel to the heme plane with the FeN(NO) and FeO(NO) distances being 2.00 and 2.61 Å, respectively.[16c] The metrical parameters of the FeNO unit for this unusual conformer (FeN 2.0 Å, FeO 2.6 Å, and ∠FeNO 110°)[16c] are very similar to those obtained here in the optimized out-of-phase tilted and bent structure of $[Fe(P)(\eta^2\text{-NO})(\text{imidazole})]^+$ (FeN 1.97 Å, FeO 2.50 Å, and ∠FeNO 102.7°). Although we have not yet characterized the optimized structures with vibrational analyses, the calculated structures and the crystallographic determination of nitrophorin 4 strongly suggest that the *out-of-phase tilted and bent FeNO geometries do correspond to true local minima on the potential energy surfaces of these molecules*. Indeed, the upright or in-phase tilted and bent geometries on one hand and the out-of-phase tilted and bent geometries on the other hand may be regarded as unique examples of "bond angle isomerism". In contrast to the $\{MNO\}^6$ complexes, the $\{MNO\}^7$ and $\{MNO\}^8$ complexes do not exhibit comparable structural flexibility and η^2-NO starting geometries open up in the course of geometry optimization to give highly reproducible in-phase tilted and bent η^1-NO optimized structures.

While a detailed molecular orbital[30] description of different metalloporphyrin−NO linkage isomers is being worked out, here we only briefly suggest a reason as to why an $\{MNO\}^6$ electron count may be important for stabilization of the η^2-NO coordination mode. More specifically, why does the three-membered $\{M(\eta^2\text{-NO})\}^n$ ring open up for $n = 7, 8$? The shape of the LUMO of $[Fe(P)(NO)]^+$ affords insight into this question. For the η^2 coordination mode, this MO is both bonding and antibonding with respect to the metal(d_{z2})−NO(π^*) orbital interaction, as shown schematically below. On addition of an electron into this MO, as in $[Fe(P)(NO)]^0$, the MNO unit opens up, preserving only the metal(d_{z2})−NO(π^*) bonding interaction.



In conclusion, we have used DFT calculations to explore the complex conformational landscapes of some representative metalloporphyrin−NO complexes, including the possibility of the phenomenon of linkage isomerism. A key conclusion is that an $\{MNO\}^6$ electron count appears to be important for stabilization of the η^2-NO coordination mode. However, for $\{FeNO\}^6$ complexes with axial ligands, a true η^2-NO coordination mode is not seen. Instead, we have identified an unusual out-of-phase tilted and bent isomer as a minimum on the $\{FeNO\}^6$ potential energy surface, in addition to the ordinary upright or in-phase tilted and bent $\{Fe(\eta^1\text{-NO})\}^6$ isomer. We propose that both the in-phase and out-of-phase tilted and bent linkage isomers—which may be regarded as unique "bond angle isomers"—may actually have been observed in a recent crystallographic determination of nitrophorin 4.

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Supporting Information Available: Tables S1−S3 (selected geometry parameters of optimized structures; complete sets of optimized Cartesian coordinates) (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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(30) For some of the "classical" quantum chemical chemical studies on metalloporphyrin−NO complexes, see, e.g.: (a) Hoffmann, R.; Chen, M. M. L.; Elian, M.; Rossi, A. R.; Mingos, D. M. P. *Inorg. Chem.* **1974**, *13*, 2666. (b) Wayland, B. B.; Olson, L. W. *J. Am. Chem. Soc.* **1974**, *96*, 6037.