Available online at www.sciencedirect.com
ScienceDirect
Coordination Chemistry Reviews 252 (2008) 1486–1496
COORDINATION CHEMISTRY REVIEWS
www.elsevier.com/locate/ccr

Review

FTIR and optical spectroscopic studies of the reactions of heme models with nitric oxide and other NO_x in porous layered solids

Tigran S. Kurtikyan [a,b,**], Peter C. Ford [c,*]

[a] *Molecule Structure Research Centre (MSRC) NAS, 375014 Yerevan, Armenia*
[b] *Research Institute of Applied Chemistry (ARIAC), 375053 Yerevan, Armenia*
[c] *Department of Chemistry and Biochemistry, University of California, Santa Barbara, Santa Barbara, CA 93106-9510 USA*

Received 9 August 2007; accepted 13 October 2007
Available online 22 October 2007

Contents

Abstract

Porous layered solids can be prepared by the vacuum sublimation of the ferrous porphyrin complexes Fe(Por) onto a CaF_2 or KBr substrate in a cryostat. The facile reactions of these heme models with volatile reactants can be studied in detail using FTIR and optical spectroscopy. The power of this technique draws from the ability to investigate such processes under carefully controlled and tunable conditions, especially temperature. Furthermore, the solvent-free medium gives relatively sharp bands in the FTIR spectra that, combined with isotopic labeling experiments, provide structural information regarding otherwise elusive intermediates and insight into key mechanistic steps. Reviewed here are investigations of the reactions between various Fe(Por) and the nitrogen oxides NO and NO_2 to give (initially) such species as Fe(Por)(NO), Fe(Por)(η^1-ONO) and Fe(Por)(η^2-O_2NO). Also described are subsequent transformations of these upon exposure to NO, NO_2 and various Lewis bases. These simple models provide fundamental information relevant to the reactions of heme proteins with the biologically important nitrogen oxides.

Keywords: Iron; Porphyrin; Nitric oxide; Nitrogen monoxide; Nitrogen dioxide; Nitrite; Nitrate; Heme

Abbreviations: 18-C-6, 18-crown-6(1,4,7,10,13, 16-hexaoxacyclooctadecane); DFT, density functional theory; FTIR, Fourier transform infrared spectroscopy; 1-MeIm, 1-methylimidazole; metHb, met-hemoglobin; MetMb, met-myoglobin; MPyTPP, dianion of *meso*-mono-4-pyridyl-triphenylporphyrin; OEP, dianion of octaethylporphyrin; P, dianion of porphine; Por, dianion of *meso*-tetraarylporphyrins; Py, pyridine; THF, tetrahydrofuran; TMP, dianion of *meso*-tetramesitylporphyrin; TPP, dianion of *meso*-tetraphenylporphyrin; TpivPP, dianion of *meso*-α,α,α,α-tetrakis(*o*-pivalamidophenyl)porphyrin; TTP, dianion of *meso*-tetra-*p*-tolylporphyrin; TmTP, dianion of *meso*-tetra-*m*-tolylporphyrin.

* Corresponding author. Tel.: +1 805 893 2443; fax: +1 805 893 4120.
** Corresponding author. Tel.: +3741 287423; fax: +3741 282267.
E-mail addresses: kurto@netsys.am (T.S. Kurtikyan), ford@chem.ucsb.edu (P.C. Ford).

0010-8545/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.ccr.2007.10.012

1. Introduction

1.1. The technique and what it does

Iron porphyrinato complexes are models for the heme proteins that perform numerous important functions in living systems. In many cases these proteins function by forming complexes via coordination of various ligands at the metal center followed by reactions at that site. In order to elucidate such processes it is crucial to have physical methods to probe effectively the nature of the intermediates formed. Vibrational spectroscopy is one such tool, and Raman and resonance Raman spectroscopy in particular have provided valuable information regarding the reactions of heme models and proteins. In contrast, infrared spectroscopic techniques, which are complementary, are often limited by solvent interference and other absorbances that mask key frequencies. Described here is a methodology that allows one to explore the reactions of simple heme model systems with volatile reagents such as nitric oxide (nitrogen monoxide), nitrogen dioxide and Lewis bases, added in specific sequences, and studied at tunable and carefully controlled temperatures in a solvent-free environment. These observations provide valuable insight into the nature of metal porphyrinato complexes relevant to the bioregulatory and other physiological roles of the nitrogen oxides.

The method involves preparation of amorphous, microporous layers of metallo porphyrinato complexes M(Por) (M = Fe(II), Mn(II) or other M(II); Por = *meso*-tetraarylporphyrinato dianion) by sublimation onto a substrate cooled by liquid nitrogen [1]. The Fe(II) porphyrinates are very oxygen sensitive, so the less sensitive Fe(Por)$(L)_2$ complexes with L = pyridine or piperidine are used as parent compounds. The low temperature sublimate is prepared [2–4] by placing Fe(Por)$(L)_2$ in a Knudsen cell and heating to ~470 K under vacuum ($P = 3 \times 10^{-5}$ Torr) to eliminate the axial ligands. Liquid nitrogen is then poured into the cryostat, and the Knudsen cell is heated to 500–550 K at which temperature sublimation of Fe(Por) onto the KBr or CaF_2 substrate occurs. The M(Por) layers obtained by sublimation onto a 77 K surface are sponge-like [5] with high microporosity that allows unimpeded diffusion of volatile ligands into the bulk of layer. Adducts formed in this manner display well-resolved FTIR spectra without solvent interference (Fig. 1, Por = TPP = *meso*-tetraphenylporphyrinato dianion). Ligands can be introduced into the cryostat at different layer temperatures, and FTIR and optical spectra of the samples can be measured over a range of specified, thermocouple-controlled temperatures (77–400 K). Notably, the use of a high vacuum technique for the introduction of various reactants significantly reduces the likelihood of introducing unintended impurities.

Examining the FTIR and optical spectra of the complexes prepared in this manner allows one to identify the species initially formed and to characterize subsequent transformations. For reactions with the nitrogen oxides, the use of isotopically labeled nitric oxide and nitrogen dioxide helps to confirm assignments. The earlier, detailed analysis of five- and six-coordinate Fe(TPP) complexes by Nakamoto and coworkers [7] showed that the IR spectra displays several bands indicative of the spin and oxidation states. During subsequent studies, we have demonstrated that similar effects are seen for other *meso*-tetraarylporphyrinato complexes. In this review we have collected data obtained by the sublimed layers methodology and discuss these in the context of the interactions between nitrogen oxides and ferrous and ferric heme models.

1.2. Why study heme reactions with the nitrogen oxides?

Nitric oxide has several well-established roles in mammalian biology closely tied to its interactions with metalloproteins, especially heme proteins [8]. A key example is the vasodilation triggered by the interaction of NO with the ferroheme center of soluble-guanylyl cyclase. Numerous heme proteins have known or proposed roles in the physiology and pathology of the nitrogen oxides. These include guanylyl cyclase, the nitric oxide synthases, hemoglobin and myoglobin among others [9,10]. In this context, there is a continuing interest in the biological pathways involving NO and other NO_x species, such as nitrogen dioxide, nitrite ion (NO_2^-) and nitrate ion (NO_3^-). For example, NO_2, formed under conditions of oxidative stress [11,12], as well as being the product of NO autoxidation in a hydrophobic envi-

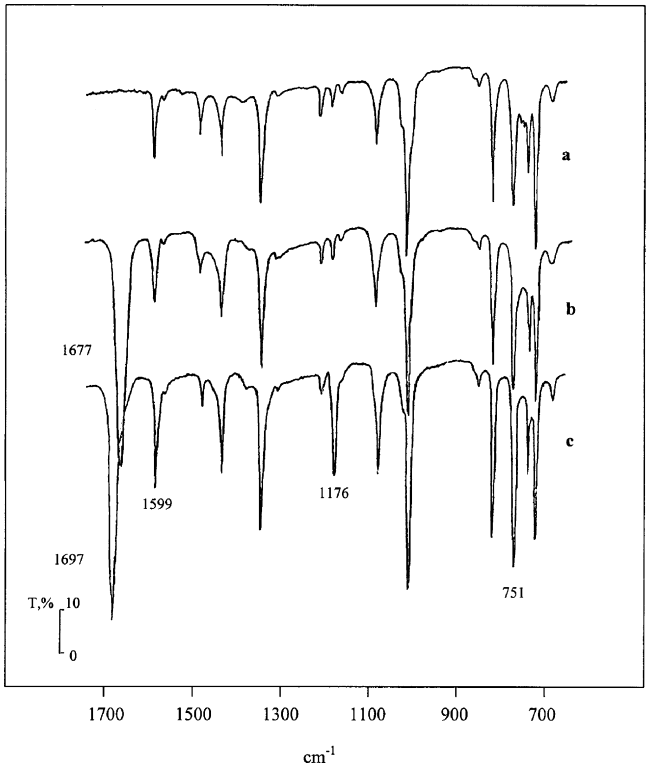


Fig. 1. This figure illustrates the high-resolution FTIR spectra that can be obtained for the various simple heme models in sublimed layers and the differences that are observed when a system is allowed to react with various reagents. The top spectrum (a) is that of a thin layer of Fe(TPP) obtained by sublimation onto low-temperature (77 K) substrate then heated to 293 K. The middle spectrum (b) is the product after the above amorphous layer reacts with excess NO. The ν(NO) band of the Fe(II) coordinated nitrosyl is clearly evident at 1677 cm^{-1}. The bottom spectrum (c) shows that annealing by heating the substrate to 353 K for 2 h then cooling to 293 K gives a more crystalline layered structure of the porphyrinato complex and that this leads to a shift in the ν(NO) band to 1697 cm^{-1} (with permission from Ref. [6]).

ronment [13,14], is a strong oxidant and nitrating species that initiates destructive pathways in living systems [15–17]. In contrast, NO_2^- is ubiquitous in mammalian tissues and fluids [18] and is the largest reservoir of accessible NO equivalents in the cardiovascular system [19].

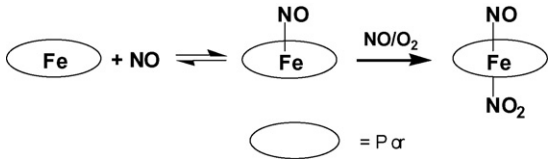
In mammalian systems, NO_3^- is generally considered a relatively unreactive end-product of nitrogen metabolism that is excreted [20]. However, there are several issues involving human health including infantile methemoglobinemia (attributed to excessive dietary nitrate reduced by intestinal bacteria) [20] and the bacterial reduction in saliva of nitrate to nitrite that is then ingested [21] that have drawn attention. In addition, as will be discussed below, nitrate can be activated by heme models to produce other highly reactive NO_x species [22], and such processes have potential relevance to the chemical biology of the nitrogen oxides. Combinations of redox active metal complexes and nitrogen oxides have also proved to be effective mediators in schemes for catalytic oxidations of various substrates [23–25].

Despite substantial progress in understanding the biological functions of various nitrogen oxides, the details of redox processes taking place in the active center of heme proteins with participation of NO_x species need further elucidation. Specifically, there is continuing incentive to elucidate the fundamental chemistry of the nitrogen oxides related to their interactions with heme models.

2. Interaction of nitric oxide with sublimed layers of metalloporphyrins

The reactions of NO with the simple ferrous heme models Fe(Por) have been studied in several laboratories. For example, Yoshimura [26] described the final product of the benzene, dichloromethane and chloroform solution reactions of Fe(TPP)(NO) with NO as the nitro nitrosyl complex Fe(TPP)(NO_2)(NO), and others have confirmed this observation [27,28]. One potential pathway leading to such a product would be a metal promoted NO disproportionation, given that a similar reaction has been demonstrated for homologous ruthenium complexes Ru(Por)(CO) exposed to excess NO. In the latter case, the products were the nitrito-nitrosyl Ru(Por)(ONO)(NO) plus nitrous oxide N_2O [29–32]. However, Lorkovic and coworkers found that, for the Fe(Por) system (Por = TPP or TmTP, *meso*-tetra-*m*-tolylporphyrinato dianion), the only product in carefully deaerated, room temperature toluene solutions under excess, carefully purified, NO [33], is the mononitrosyl adduct Fe(Por)(NO) and that disproportionation was at best a very minor pathway [34]. Moreover, at low temperature, a second nitrosyl adds reversibly (Eq. (1)) to give the dinitrosyl complexes Fe(Por)$(NO)_2$ ($K_1 = 3100$ at 179 *K*, $\Delta H = -6.7$ kcal mol^{-1}) as observed by FTIR and NMR spectroscopy [35] and evaluated by DFT computations [36,37]. However, when trace quantities of air were introduced, rapid formation of the nitro nitrosyl complex was observed. Thus, contamination by air or other NO_x was concluded to be the source of the nitro nitrosyl complexes [36]:

$$\text{Fe(Por)(NO)} + \text{NO} \overset{K_1}{\rightleftharpoons} \text{Fe(Por)(NO)}_2 \quad (1)$$



Scheme 1.

This system was reexamined by using the sublimed layer technique to probe intermediates in the reaction of NO with sublimed layers of Fe(TPP) [6]. Addition of NO to Fe(TPP) at room temperature gave the mononitrosyl complex Fe(TPP)(NO) with a ν(NO) of 1677 cm^{-1} (1646 cm^{-1} for ^{15}NO) in the sublimed amorphous layer (see Fig. 1b), and no further reaction was seen by the FTIR or optical absorbance measurements under these conditions. However, when the temperature was lowered to 170 K with excess NO present, the dinitrosyl complex Fe(TPP)$(NO)_2$ with ν(NO) band at 1684 cm^{-1} (with an intensity about twice that of Fe(TPP)(NO)) was formed reversibly. No further transformations were seen according to FTIR measurements [6]. These observations are in agreement with the earlier solution phase study [34] as was the result that introducing trace O_2 to the sublimed layer led to formation of Fe(Por)(NO_2)(NO) (Scheme 1).

The NO stretching frequencies ν(NO) for various complexes are summarized in a table appearing later in this review.

In contrast to the behavior of Fe(Por), the NO-disproportionation reaction was facile in porous layers with the ruthenium(II) analog Ru(TPP), resulting directly in formation of Ru(TPP)(NO)(η^1-ONO) (Eq. (2)) [6]. The much greater propensity to favor disproportionation in this case can be attributed to the lower stability (relative to iron analogs) of the Ru(II) nitrosyl complex Ru(Por)(NO) and the greater tendency to form the dinitrosyls Ru(Por)$(NO)_2$ at ambient temperatures. Notably, the manganese(II) analogs Mn(Por) (Por = TPP, perdeuterio-tetraphenylporphyrinato dianion (TPP-d_{20}) or tetramesitylporphyrinato dianion (TMP)) also show a high propensity toward NO disproportionation [38]. The NO interaction with sublimed layers of Mn(Por) resulted eventually in formation of Mn(Por)(η^1-ONO) and evolution of nitrous oxide N_2O. At low temperatures, the nitrito-nitrosyl complex Mn(Por)(η^1-ONO)(NO) was spectroscopically characterized, but this lost the coordinated NO upon warming to room temperature (Eq. (3)) [39]:

$$\text{Ru(Por)} + 4\text{NO} \rightarrow \text{Ru(Por)(ONO)(NO)} + \text{N}_2\text{O} \quad (2)$$

$$\text{Mn(Por)} + 4\text{NO} \rightarrow \text{Mn(Por)(ONO)(NO)} + \text{N}_2\text{O} \rightleftharpoons \text{Mn(Por)(ONO)} + \text{NO} \quad (3)$$

3. Nitrite complexes of iron(III) porphyrins

3.1. The five-coordinate nitrito complexes of iron porphyrins

As noted in the introduction, there has been considerable interest and some controversy regarding the potential roles of

nitrite in mammalian cardiovascular biology [19,40,41]. Regardless of the eventual outcome, much of the discussion regarding nitrite ion activity revolves around its interactions with heme proteins. As a consequence, the structure and reactivity of the nitrito complexes of heme iron are of considerable interest.

There are several modes by which nitrite ion as an ambidentate ligand may bind to metal centers to form nitro (N-coordinated, M-NO_2) and nitrito (O-coordinated, M-ONO) complexes as well as the bidentate coordinated linkage isomer M(η^2-O_2N) [42]. Before 2004, characterized NO_2^- complexes of synthetic ferrous or ferric porphyrinato complexes [29] or of heme proteins [43–45] were mostly nitro-isomers. An exception would be the anion of [K(222)]-[Fe(TpivPP)(NO_2)(NO)] (TpivPP = *meso*-tetrakis(*o*-pivalamidophenyl)porphyrinato dianion) prepared by the reaction of Fe(TpivPP) with Kryptofix-222 solubilized KNO_2 followed by the reaction with NO. This product had two crystalline forms; in one the nitro nitrosyl structure Fe(TpivPP)(NO_2)$(NO)^-$ anion was evident, but the other had two independent anions in the asymmetric unit, one of which was disordered, apparently as the result of both linkage isomers being present [46]. For the picket fence porphyrinato complexes structural [47] and computational [48] analyses of the six-coordinate complex Fe(TPivPP)(NO_2)(Py) suggest that weak hydrogen bonding between O-atoms of nitro group and picket fence NH groups may stabilize this linkage isomer.

There are now several other examples of nitrito heme complexes [49–52]. For example, photolysis of Fe(TPP)(NO_2)(NO) in a low temperature KBr pellet leads to a metastable compound that was concluded to be the nitrito-nitrosyl complex Fe(TPP)(η^1-ONO)(NO). This assignment was based on IR spectra displaying N-isotope sensitive ν(N=O) and ν(N–O) stretching modes characteristic of a Fe–O–N=O structure at 1507 and 934 cm^{-1} and on extensive DFT calculations [49,50]. In addition, a nitrite ion complex prepared by the soaking crystals of horse heart met-myoglobin (metMb) in $NaNO_2$ solution gave a crystal structure that clearly shows the NO_2^- ligand coordinated as the O-bound nitrito isomer [51].

Along these lines, the sublimed layer technique was used to examine the reaction of NO_2 with Fe(Por) (Por = TPP, or *meso*-tetra-*p*-tolylporphyrinato dianion, TTP). This reaction gave products that were characterized spectroscopically as the five-coordinate ferric nitrito complexes Fe(Por)(η^1-ONO) (Scheme 2) [52]. Such species had been proposed as reactive intermediates but had not been well characterized in earlier studies [53]. These products were identified [52] as the O-coordinated nitrito isomers from the FTIR spectra revealing three new bands in the vicinity of 1525 cm^{-1} {ν(N=O)}, 900 cm^{-1} {ν(N–O)} and 750 cm^{-1} {δ(ONO)} and as high spin Fe(III) from the optical spectra and shifts in spin-sensitive porphyrin vibrations [7]. The Fe(Por)(η^1-ONO) species prepared in this manner proved to be fairly stable in the solid state, although under vacuum they slowly decomposed (in a few days) to give, mostly, the respective Fe(Por)(NO) complexes with a strong ν(NO) band in the vicinity of 1675 cm^{-1}.

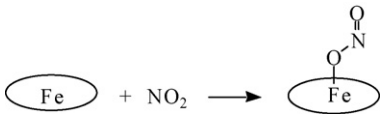
DFT computations at the B3LYP/LACVP* level suggest [54] that the nitrito and nitro linkage isomers Fe(P)(ONO) and Fe(P)(NO_2) (P = the unsubstituted porphinato dianion) have similar energies with the nitrito species more stable, but only by less than 1 kJ mol^{-1}. Despite this, the experimental studies showed only the former to be present as the initial product from the reaction of NO_2 with Fe(TPP) or Fe(TTP) in layered solids. One rationalization would be that the nitro isomer Fe(Por)(NO_2) may be destabilized by the *meso* aromatic substituents of TPP and TTP or by interactions in the polarizable condensed phase not accounted for in the (gas phase) DFT computations of the simpler porphinato complexes.

3.2. The interaction of Fe(Por)(ONO) with nitric oxide

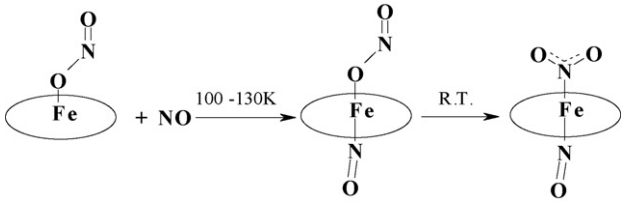
The room temperature reaction of NO gas with sublimed layers containing pre-formed Fe(Por)(ONO) (Por = TPP or TTP) leads to rapid formation of the familiar nitro-nitrosyl complexes Fe(Por)(NO_2)(NO) [54]. However, at low temperature (130 K), the reaction nearly quantitatively forms nitrosyl complexes identified as the nitrito isomers Fe(Por)(η^1-ONO)(NO) owing to the characteristic and isotope sensitive nitrosyl and nitrito bands in the vicinity of 1890 cm^{-1} {ν(NO)}, 1500 cm^{-1} {ν(N=O)} and 935 cm^{-1} {ν(N–O)}. As noted above, the analogous species was identified as one of the metastable species formed upon photolysis of a low temperature KBr pellet containing Fe(TPP)(NO_2)(NO) [49,50].

Upon warming the Fe(TPP)(ONO)(NO) sample from 130 to 220 K, the FTIR spectra underwent changes evidencing formation of the nitro-nitrosyl complex Fe(TTP)(NO_2)(NO), the Yoshimura type complex. Hence warming Fe(TTP)(η^1-ONO)(NO) results in the nitrito → nitro isomerization of coordinated NO_2 (Scheme 3) as demonstrated by the disappearance of the nitrito bands at 1497 and 935 cm^{-1} and appearance of new bands at 1456 and 1293 cm^{-1} characteristic of a nitro complex [54]. This process proceeds in the presence of excess NO as well as after evacuating the NO from the cryostat system at 130 K before warming the Fe(Por)(ONO)(NO) layer on the substrate.

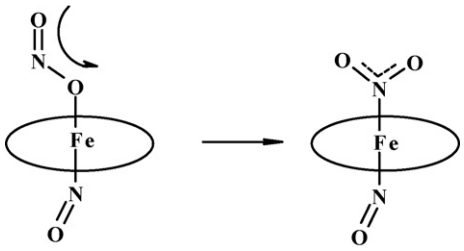
This linkage isomerization was also probed using optical spectroscopy; however, the differences between the UV–visible spectrum of the nitrito-nitrosyl complex and that of the nitro-



Scheme 2. Formation of nitrito complexes by reaction of NO_2 with Fe(Por) in sublimed layers.



Scheme 3. Formation of Fe(Por)(ONO)(NO) and its isomerization to Fe(Por)(NO_2)(NO).

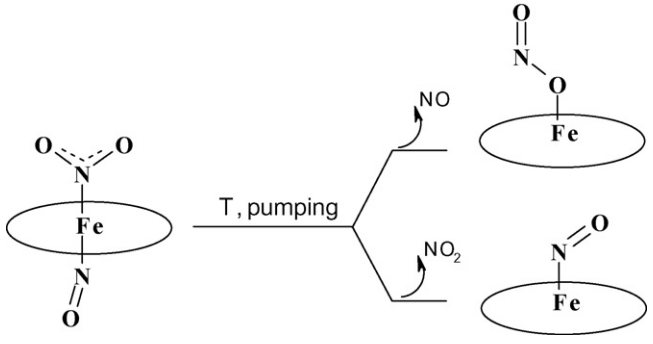


Scheme 4. Intramolecular isomerization of Fe(Por)(ONO)(NO), the "flipping" mechanism.

nitrosyl analog are too small to differentiate between the two isomers [54]. This spectral similarity may explain why the oft-postulated nitrito-nitrosyl isomer had not been characterized previously by optical spectroscopy. It is also worth noting that interaction of NO with sublimed layers of Fe(Por)(ONO) at the intermediate temperature 170 K leads to the formation of both Fe(Por)(ONO)(NO) and Fe(Por)(NO_2)(NO) isomers in comparable quantities. In contrast to the Fe(Por)(ONO) complexes, both isomeric forms of the NO adducts are in the low-spin state.

By action of ^{15}NO gas with the layered Fe(Por)(ONO) and vice versa by action of NO with Fe(Por)(O^{15}NO), it was possible to obtain the complexes with the differently labeled nitrogen oxides in the axial positions, namely Fe(Por)(ONO)(^{15}NO) and Fe(Por)(O^{15}NO)(NO). Such mixed-isotope species provide interesting mechanistic probes but cannot be prepared specifically in solution experiments due to isotope scrambling. By using these materials, it was shown that isomerization of the nitrito-nitrosyl complexes into their nitro-nitrosyl analogs in the sublimed solids does not proceed via NO_2 dissociation, but instead involves an intramolecular mechanism as illustrated in Scheme 4.

In room temperature solutions, the nitro-nitrosyl complexes Fe(Por)(NO_2)(NO) are stable only under excess NO and undergo serial transformations to different NO_x species (see below). In contrast when the Fe(Por)(NO_2)(NO) prepared as a solid layer in the cryostat is subjected to intense high vacuum pumping, Fe(Por)(NO) and Fe(Por)(ONO) are the two products formed. This indicates that the nitro isomer Fe(Por)(NO_2)(NO) is labile toward competitive dissociation both of NO and of NO_2 under these conditions (Scheme 5). Although loss of NO would give the five-coordinate nitro complex Fe(TTP)(NO_2), this apparently isomerizes to the more stable nitrito form. Spontaneous



Scheme 5. Competitive dissociation of NO and NO_2 ligand from nitro-nitrosyl complex of iron-porphyrins Fe(Por)(NO_2)(NO).

NO dissociation from Fe(Por)(NO_2)(NO) has been observed in ambient temperature toluene solutions as well [53].

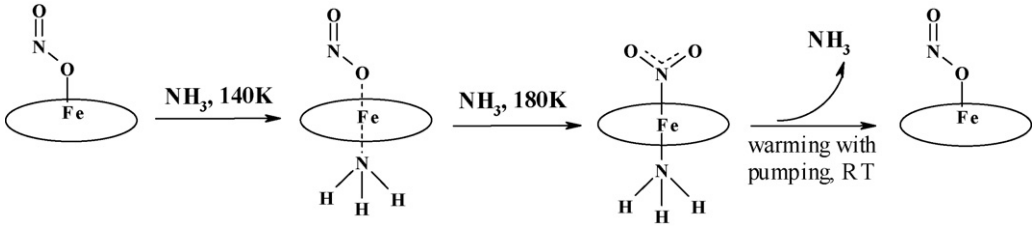
3.3. The interaction of Fe(Por)(ONO) with nitrogen bases

Exposure of Fe(Por)(ONO) in room temperature solids to vapors of various Lewis bases L (L = ammonia, pyridine or 1-methylimidazole) leads to immediate coordination to give nitro complexes of general formula Fe(Por)(L)(NO_2) [55]. These reveal different thermal stabilities depending on the nature of L. The ammonia complex is stable only when excess NH_3 (>20 Torr) is present, the pyridine complex slowly dissociates Py over a few days under vacuum, while the 1-MeIm complex is indefinitely stable. Furthermore, Fe(Por)(1-MeIm)(NO_2) is relatively stable even in dry solution (toluene, chloroform and dichloromethane were tested), where it survived several hours before decomposing. According to the positions of spin-sensitive FTIR bands all these six-coordinate compounds are in the low-spin state.

The instability of nitrite ferric porphyrinato complexes [56] has been addressed by using picket fence porphyrinato (TpivPP) complexes where the coordinated nitrite is protected in the pocket formed by four pivalamido residues [57]. The bis(nitrite) species [K(18-C-6)(H_2O)][Fe(TpivPP)(NO_2)$_2$] were prepared and structurally characterized by Scheidt and coworkers [57], and used as a precursor for the synthesis of mixed ligand nitrite ion complexes with *trans* axial N- and S-donor ligands [58,59] with a nitro ligand in the protected site. In this context, the sublimed solid layer technique reviewed here allows one to characterize six-coordinate nitro complexes prepared from the five-coordinate nitrito Fe(Por)(ONO) precursors even for sterically unprotected porphyrins.

Scheme 3 illustrates the NO reaction with Fe(Por)(ONO) at low temperature to form, first, the nitrito-nitrosyl complex Fe(Por)(ONO)(NO), which isomerizes to the nitro analog Fe(Por)(NO_2)(NO) upon warming [54]. Thus, it was of interest to evaluate whether a similar six-coordinate nitrito species might be an intermediate in the reaction with a Lewis base. For this purpose NH_3 was introduced to the cryostat containing Fe(Por)(η^1-ONO) in porous layers at ~77 K. The FTIR spectra were recorded to characterize the species first formed, then repeatedly during the process of slowly warming [55]. The presence of ν(N=O) and ν(N–O) bands at 1470 and 976 cm^{-1} correspondingly demonstrated the initial formation of Fe(Por)(NH_3)(ONO) at 150 K followed by isomerization to the nitro analog Fe(Por)(NH_3)(NO_2) as T increased to 200 K (Fig. 2, Scheme 6). However, the latter were stable at room temperature only with excess NH_3 (>20 Torr), so if the system was instead warmed to room temperature under an actively pumped high vacuum, the ammine complexes converted back to the penta-coordinate complex Fe(Por)(ONO) (Scheme 6). Hence, as seen with loss of NO, dissociation of the *trans* ammine results in reverse linkage isomerization [55].

Similar attempts to obtain six-coordinate nitrito complexes with L = Py or MeIm were unsuccessful [55]. Only the analogous nitro complexes were spectroscopically detected, but this is likely to be due to slower diffusion of these less volatile ligands



Scheme 6. The reaction of Fe(Por)(ONO) with NH_3.

into the porous layers of Fe(Por)(ONO) at the low temperatures where Fe(Por)(NH_3)(ONO) complexes were observed. Higher temperatures (~170 K for L = Py; ~200 K for L = 1-MeIm) were required to form complexes with these ligands; however, it was in this range that the ammonia nitrito complexes underwent linkage isomerization.

Table 1 also summarizes FTIR data for various Fe(III) six-coordinate nitrite ion complexes, for the $^{15}NO_2$ labeled isotopomers and for certain Co(III) analogs [60,61]. The data recorded for various nitro complexes M(Por)(L)(NO_2) suggest an inverse correlation between basicity of L and the frequency differences between the asymmetric and symmetric nitro group stretches, $\Delta\nu = \nu_a(NO_2) - \nu_s(NO_2)$ [55]. Within each Fe(Por)(L)(NO_2) series, $\Delta\nu$ follows the order 1-MeIm < NH_3 < Py ≪ NO, and the Co(Por)(L)(NO_2) series displays an analogous order 1-MeIm < NH_3 < Py≪no ligand. Since electronic communication between the axial ligands, L and NO_2, occurs largely through the metal d-orbitals, we propose that $\Delta\nu$ reflects the net charge transfer from L to the nitro group, with the smaller $\Delta\nu$ representing more charge transfer. For all three series, the order 1-MeIm < NH_3 < Py holds true. This does not correlate with the ligand Brönsted base strengths, where 1-MeIm is intermediate between Py and NH_3. However, the observed order may reflect the modest π-donor character of 1-MeIm, while NH_3 is a σ-donor only and Py is a π-acceptor [62]. The observation that NO displays the largest $\Delta\nu$ for the Fe(III) series is especially interesting, since it suggests that there is very little net electron transfer from NO to the nitro ligand in the complex Fe(Por)(NO)(NO_2). Such a conclusion draws support from DFT calculations (B3LYP/3–21 g and B3LYP/6–31 g) for the porphinato complex Fe(P)(NO)(NO_2) showing NO to be slightly negative, hence having a net electron withdrawing effect [63]. This runs counter to the oft-used representation of Fe(III) nitric oxide complexes as the $Fe^{II}(NO^+)$ resonance form.

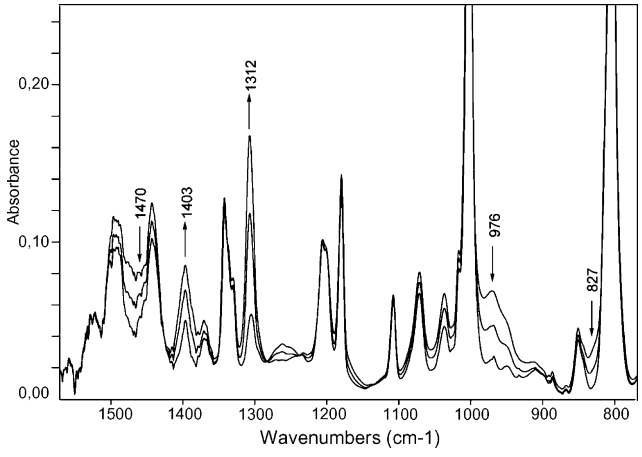


Fig. 2. FTIR spectral changes observed in sublimed layer of Fe(TTP)(ONO) in the presence of 1 Torr equivalent of NH_3 upon warming from 140 K (initial spectrum) to 170 and 200 K and removal of excess NH_3 (with permission from Ref. [55]).

The $\Delta\nu$ values are systematically higher for the Co(III) complexes than for the Fe(III) analogs suggesting less charge transfer in the former case. Since a higher value of $\Delta\nu$ corresponds a larger ONO angle [25], this is consistent with the ONO angles which are 120–124° for the Co(III) complexes [25] and are less acute seen for similar nitrito complexes of Fe(III) porphyrins (116–120°) [28].

4. Nitrato iron(III) porphyrinato complexes

4.1. Preparation in sublimed solids

The final product of the reaction of excess NO_2 with Fe(TPP) has been shown [64] to be the η^2-nitrato species Fe(TPP)(η^2-O_2NO). Similar reactivity is seen with the manganese(II) analog Mn(TPP) [65], but the cobalt(II) species Co(TPP) gave only the nitro complex Co(TPP)(NO_2) under the same experimental conditions [60,66]. The FTIR data clearly show that the NO_2 reaction with ferrous porphyrinato complexes proceeds via two distinct stages. The first, seen at low P_{NO_2}, is the formation of the five-coordinate nitrito complex Fe(Por)(ONO) described above [52]. Subsequent reaction at higher P_{NO_2} leads to the nitrato species with concomitant formation of NO as illustrated in Eq. 4 [54]:

$$\text{Fe(TPP)(ONO)} + \text{NO}_2 \rightarrow \text{Fe(TPP)}(\eta^2\text{-O}_2\text{NO}) + \text{NO} \quad (4)$$

Two possible scenarios for the second stage are depicted below. The most straightforward would be simple oxygen atom transfer from the incoming NO_2 to the nitrito ligand nitrogen atom to transform the coordinated nitrite to a coordinated nitrate as shown in Scheme 7a. An alternative pathway (Scheme 7b) would involve bond formation between the nitrogen atom of the incoming NO_2 and the coordinated O of the nitrito ligand then NO release from the originally coordinated nitrite.

Both schemes give a monodentate nitrato complex as the initial product but differ in the origin of the nitrogen atom ending up in the eventual nitrato ligand. In principle, the two mechanisms could be differentiated by isotope labeling experiments. For the first, the reaction of unlabeled Fe(Por)(ONO) with $^{15}NO_2$ would give unlabeled nitrato complex. For the second, the nitrogen of the nitrate ligand found in the product would have

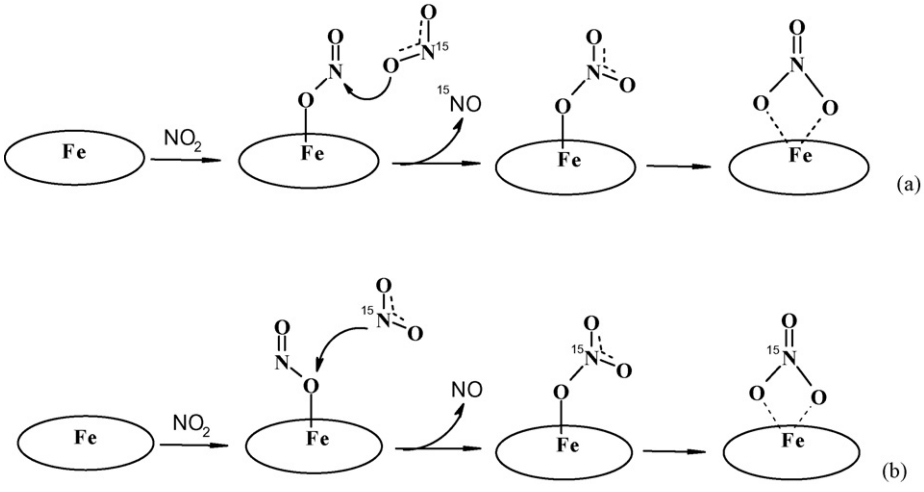
Table 1
IR frequencies of coordinated nitrosyl, nitro- or nitrito groups in metalloporphyrin complexes in sublimed solids[a] (frequencies in parentheses are those recorded for ^{15}N nitrosyl, nitro and nitrito complexes)

Compounds*	ν(NO) nitrosyl (cm^{-1})	$\nu_a(NO_2)$, ν(N=O) (cm^{-1})	$\nu_s(NO_2)$, ν(N–O) (cm^{-1})	δ(ONO), $\delta(NO_2)$ (cm^{-1})	$\Delta\nu$[b]	Ref.
Fe(TPP)(NO)	1677 (1646)					[6]
Fe(TPP)$(NO)_2$	1684 (1654)					[c]
Fe(TPP)(ONO)		1527 (1495)	901 (878)			[52]
Fe(TTP)(ONO)		1528 (1496)	902 (879)	751 (747)		[52]
Fe(TTP)(NH_3)(ONO)		1470 (1438)	969 (952)	~827 (822)		[55]
Fe(TPP)(NH_3)(ONO)		1475 (1445)	971 (952)	~828 (821)		[55]
Fe(TTP)(NO)(ONO)	1888 (1851)	1497 (1464)	935 (917)	–		[54]
Fe(TPP)(NO)(ONO)	1887 (1850)	1496 (1471)	938 (920)			[54]
Fe(TTP)(NO)(NO_2)	1860 (1824)	1456 (1424)	1293 (1274)	~805 (800)	163 (150)	[54]
Fe(TPP)(NO)(NO_2)	1863 (1824)	1455 (1425)	1295 (1274)	~805 (800)	160 (151)	[54]
Fe(TTP)$(NH_3)$$(NO_2)$		1401 (1367)	1312 (1291)	810 (~804)	89 (76)	[55]
Fe(TPP)$(NH_3)$$(NO_2)$		1399 (1373)	1312 (1291)	812 (~805)	87 (82)	[55]
Fe(TTP)(Py)(NO_2)		1405 (1373)	1306 (1287)	810 (~804)	99 (86)	[55]
Fe(TPP)(Py)(NO_2)		1406 (1379)	1307 (1287)	810 (~804)	99 (92)	[55]
Fe(TTP)(1-MeIm)(NO_2)		1396 (1363)	1312 (1291)	813 (~805)	84 (72)	[55]
Fe(TPP)(1-MeIm)(NO_2)		1395 (1371)	1312 (1290)	812 (~805)	83 (81)	[55]
Fe(TTP)(NO)(NO_2)	1860 (1824)	1455 (1423)	1295 (1275)	~805 (800)	160 (148)	[54]
Mn(TTP)(NO)(ONO)	1812 (1778)	1480 (1455)	971 (950)	822 (818)		[39]
Mn(TPP)(NO)(NO_2)	1805 (1770)	1421 (1392)	1304 (1286)	–	117 (106)	[38]
Ru(TPP)$(NO)_2$	1645 (1608)					[c]
Ru(TPP)(NO)(ONO)	1844 (1810)	1516 (1492)	928 (908)			[6]
Co(TPP)$(NH_3)$$(NO_2)$		1431 (1400)	1309 (1289)	814 (805)	122 (111)	[61]
Co(TPP)(Py)(NO_2)		~1439 (1404)	1310 (1288)	816 (806)	129 (116)	[61]
Co(TPP)(1-MeIm)(NO_2)		1420 (1394)	1313 (1292)	816 (809)	107 (102)	[c]
Co(TPP)(NO_2)		1468 (~1440)	1282 (1264)	~805 (796)	186 (176)	[60]

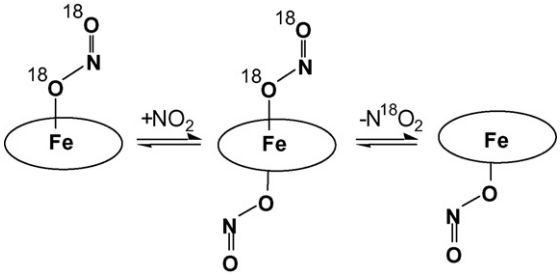
[a] Six-coordinate complexes having the nitrito ligand as well as Mn(Por)(NO_2)(NO) are stable only at low temperatures.
[b] $\Delta\nu = \nu_a(NO_2) - \nu_s(NO_2)$.
[c] Unpublished results.

originated with the gaseous $^{15}NO_2$ giving the labeled product Fe(Por)(η^2-$O_2{}^{15}$NO). Such analysis was, however, complicated by the discovery that exchange between external and coordinated nitrogen dioxide occurs concomitant to the second stage of the reaction [54]. Despite this, the observation that the $^{15}NO_2$ reaction with unlabeled Fe(Por)(ONO) gives some unlabeled nitrato product initially argues for the operation of the first mechanism, at least partially.

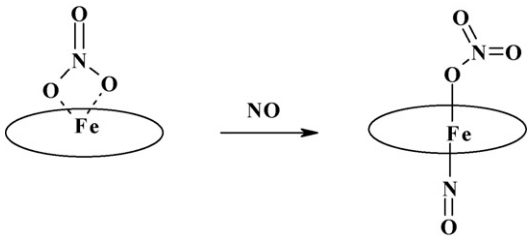
A likely pathway for the NO_2 exchange would involve reaction at the open coordination site of Fe(Por)(ONO) to give a transient bis(nitrito) complex or one of its isomers as an intermediate (Scheme 8). This pathway would be analogous to the exchange of free and coordinated NO demonstrated for Fe(Por)(NO) complexes [26,67]. For example, sublimed solid Fe(MPyTPP) (MPyTPP = mono-4-pyridyltriphenylporphyrinato dianion) reacts with NO to form a



Scheme 7. Prospective mechanism for formation of Fe(Por)(η^2-O_2NO) by the oxo-transfer from free NO_2 to Fe(Por)(ONO) (a) and by the NO_2 attack at the coordinated O-atom of Fe(Por)(ONO).



Scheme 8. Possible mechanism for exchange of Fe(Por)(^{18}ON^{18}O) with added NO_2.



Scheme 9. Formation of six-coordinate nitrato-nitrosyl complex Fe(TPP)(η^1-ONO_2)(NO) upon low-temperature interaction of NO gas with Fe(TPP)(η^2-O_2NO).

mixture of Fe(MPyTPP)(NO) and *trans*-Fe(MPyTPP)(L)(NO), where L is a pyridyl from an adjacent Fe(MPyTPP) [68]. Addition of labeled NO to this mixture gave exchange only with the five-coordinate species, thus an empty coordination site is necessary to access the dinitrosyl intermediate *trans*-Fe(Por)$(NO)_2$ [35,36]. DFT computations [54] support an analogous pathway as an energetically reasonable mechanism for the NO_2 exchange with the porphinato model Fe(P)(NO_2) and indicate that the lowest energy isomer of the intermediate in Scheme 8 is the triplet bis(nitro) complex ^{3}Fe(P)$(NO_2)_2$, although the bis(nitrito) analog ^{3}Fe(P)$(ONO)_2$ is less than 5 kJ mol^{-1} above this.

Rudkevich and coworkers [69] have reported that Ru(TTP)(CO) reacts with NO_2 in CH_2Cl_2 solution to give the nitrato-nitrosyl complex Ru(TTP)(NO_3)(NO). Although it was proposed that this occurs via N_2O_4 disproportionation to nitrosonium nitrate $NO^+NO_3^-$, such a pathway is unlikely for the sublimed solids experiments given the low P_{NO_2} and the absence of a solvent to support ionic intermediates. On the other hand, the pathway described for Fe(Por) appears to be a reasonable alternative mechanism for Ru(TTP)(CO). NO_2 coordination would give Ru(TTP)(CO)(NO_2), formally a Ru(III) species, which would be susceptible to CO dissociation. Subsequent reaction with NO_2 would give the nitrato complex Ru(TTP)(NO_3) plus NO, which could combine to give Ru(TTP)(NO_3)(NO).

4.2. Six-coordinate nitrato complexes

In coordination complexes containing nitrate groups the latter can be present as the free ion, as a mono- or bidentate O-bound ligand as well as a bridging species of different kinds. IR spectroscopy is useful probe for distinguishing these modes of interactions [70].

According to structural data the nitrato ligand of Fe^{III}(TPP)(η^2-O_2NO) is bidentate [71], and the Fe(III) is in the high-spin state with a large out-of-plane displacement (0.6 Å) toward the coordinated nitrate. The energy difference between bidentate and monodentate coordination must be small given that the octaethylporphyrinato analog Fe^{III}(OEP)(η^1-ONO_2) is monodentate [72], and this view is supported by DFT computations with the porphinato complex Fe(P)(NO_3). While one might expect the heme complexes to be susceptible to binding a ligand in the axial site *trans* to the nitrato ligand, examples of such six-coordinate complexes were limited to the aqua complex Fe(P)(H_2O)(η^1-ONO_2) (P not identified) described in a review by Wyllie and Scheidt [28].

The low-temperature (160 K) interaction of NO with sublimed layers of the nitrato complex Fe(TPP)(η^2-O_2NO) leads to appearance of an intense band at 1901 cm^{-1}, consistent with the ν(NO) of Fe(III) coordinated nitric oxide. The nitrato bands undergo shifts that are interpreted in terms of bidentate to monodentate isomerization. Additionally the spin-sensitive bands at 1351 and 464 cm^{-1} are characteristic of the formation of a low-spin complex. These data together with the optical spectral changes indicate [73] the formation of the six-coordinate Fe(TPP)(η^1-ONO_2)(NO) (Scheme 9). This product is stable only below 200 K. When warmed, subsequent reactions lead to several species, the relative quantities being a function of the NO pressure. These transformations will be considered further in the next section.

The analogous low temperature (150 K) reaction of sublimed layers of Fe(Por)(η^2-O_2NO) with THF leads to changes in the FTIR and optical spectra that indicate formation of six-coordinate nitrato complexes [74]. *Trans* ligation was accompanied by a shift from bidentate to monodentate coordination of the nitrato ligand, but this adduct remains high spin unlike the NO adduct, which is low-spin. Although thermally unstable these six-coordinate nitrato adducts obviously can figure as intermediates in the reactions of iron-porphyrins *in vitro* and *in vivo*.

With the stronger donor ammonia, a different pattern was seen; the coordinated nitrate ion proved to be labile [74]. Exposure of Fe(Por)(η^2-O_2NO) in solid layers to excess NH_3 at 180 K led to the disappearance of the IR bands characteristic of the coordinated nitrate and to the appearance of a strong absorbance at ~1370 cm^{-1} (~1340 cm^{-1} for ^{15}N-labeled species), which can be attributed to the intense ν_3(E) vibration of free nitrate ion ($^{15}NO_3^-$) in the matrix. Vigorous pumping of the system led to regeneration of nitrato complex, so the likely scenario is represented by Eq. (5). Notably this does not appear to occur in reactions with the weaker base THF:

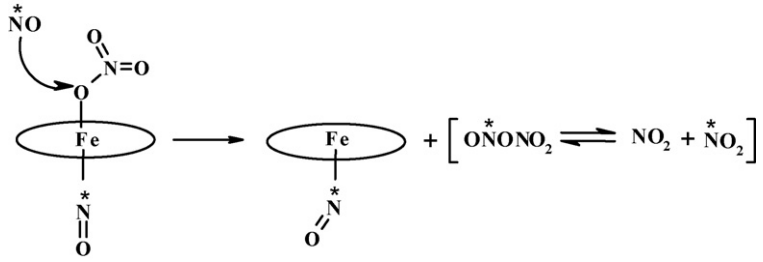
$$\text{Fe(TPP)}(\eta^2\text{-O}_2\text{NO}) + 2\text{NH}_3 \rightleftharpoons \text{Fe(TPP)}(\text{NH}_3)_2^+ : \text{NO}_3^- \quad (5)$$

FTIR spectral data for five- and six-coordinate nitrato complexes are summarized in Table 2.

Table 2
FTIR spectral data[a] (in cm^{-1}) for nitrosyl and nitrate groups in five- and six-coordinate nitrato complexes of iron-porphyrins

Compound	ν(N≡O)	ν(N═O)	$\nu_a(NO_2)$	$\nu_s(NO_2)$	ν(N–O)	Ref.
Fe(TPP)(η^2-O_2NO)		1527 (1489)	1273 (1253)	967 (958)		[21]
Fe(TTP)(η^2-O_2NO)		1529 (1494)	1271 (1251)	966 (957)		[54]
Fe(TPP)(NO)(η^1-ONO_2)	1901 (1863)		1505 (1470)	1266 (1248)	978 (963)	[73]
Fe(TPP)(THF)(η^1-ONO_2)			1491 (1457)	1280 (1258)	997[b] (986)	[74]
Fe(TTP)(THF)(η^1-ONO_2)			1486 (1454)	1277 (1258)	995[b] (984)	[74]
Ru(TTP)(NO)(η^1-ONO_2)	1852		1515	1269	950	[69]
Mn(TPP)(η^1-ONO_2)			1473 (1434)	1286 (1260)		[65]

[a] Data in parentheses are for ^{15}N-labeled compounds.
[b] Masked by intense porphyrin band.



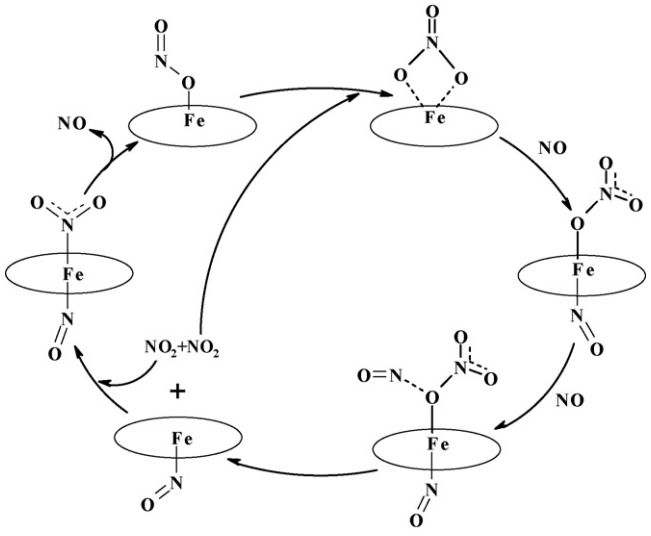
Scheme 10.

4.3. Further reaction of Fe(TPP)(NO_3)(NO) with nitric oxide

The interaction of nitric oxide with nitrato iron-porphyrins complexes is not limited to the formation of the nitrato-nitrosyl complexes Fe(Por)(η^1-ONO_2)(NO) [73]. Both in sublimed layers and in solution the interaction of Fe(Por)(η^2-O_2NO) with excess NO leads to a distribution of iron-porphyrin complexes ligated by the various nitrogen oxides [22]. The eventual products are Fe(Por)(NO), Fe(Por)(NO_2)(NO) and Fe(Por)(η^2-O_2NO), the relative quantities of which are the function of NO partial pressure.

The use of ^{15}NO helped to elucidate the mechanism of formation of Fe(TPP)(NO_2)(NO) from Fe(TPP)(η^2-O_2NO) [22]. In the beginning of the reaction, equal quantities of Fe(TPP)(NO_2)(^{15}NO) and Fe(TPP)($^{15}NO_2$)(^{15}NO) were formed. The first step must be the formation of the Fe(TPP)(η^1-ONO_2)(^{15}NO) as outlined above, followed by attack of ^{15}NO on the monodentate nitrate ligand to give singularly labeled N_2O_4 plus Fe(TPP)(^{15}NO) as illustrated in Scheme 10. This step finds analogy in the reductive nitrosation of a coordinated ligand seen with a copper(II) complex [75]. Reaction of the nitrogen dioxide formed by dissociation of the N_2O_4 with the nitrosyl complex would give the nitro nitrosyl complex with half the nitro groups labeled.

It is also notable that the nitrato complex eventually formed by interaction of ^{15}NO with Fe(TPP)(η^2-O_2NO) is not the unreacted starting material but is its isotopic analog Fe(TPP)(η^2-$O_2{}^{15}NO$). Thus, this must be the product of multiple transformations. Such observations demonstrate that the nitrate anion, which is usually considered relatively innocuous in mammalian biology, can be activated by a heme and NO. Note that this reaction would lead to formation of NO_2, a strong oxidant and nitrating agent destructive to living systems [20,21].



Scheme 11. Dynamic processes taking place with iron-porphyrins nitrato complexes in the presence of NO.

The dependence of the product distribution on the NO concentration is addressed schematically by the complicated dynamic equilibrium of reactions depicted in Scheme 11. In the presence of excess NO, the nitro-nitrosyl complex appears to be the thermodynamic sink, while the pentacoordinated Fe(Por)NO and Fe(Por)(η^2-O_2NO) are favored when less NO is present.

5. Summary

FTIR and UV–visible spectroscopy combined with the sublimed layers methodology give rich information about reactions

of nitrogen oxides with heme modeling iron-porphyrins and interconversions of these species taking place in the coordination sphere of central metal ion. The main results of these studies are summarized below:

(1) Fe(II) porphyrins do not initiate NO disproportionation reactions. Instead a dinitrosyl complex Fe(Por)$(NO)_2$ is formed at low temperatures and this complex dissociates to reform the mononitrosyl complex Fe(Por)(NO) upon warming. In contrast the Mn(II) porphyrins initiate NO disproportionation to form (eventually) the nitrite complex Mn(Por)(ONO) and N_2O. At low temperatures the intermediate nitrosyl-nitrito complex Mn(Por)((ONO)(NO) can be spectroscopically characterized.
(2) Reaction of NO_2 gas with Fe(II) porphyrins in porous solids leads to formation of pentacoordinate nitrito intermediate Fe(Por)(η^1-ONO) with the Fe(III) in a high-spin state. Using this compound as a precursor, the reaction with various ligands gives the six-coordinate nitro complexes Fe(Por)(L)(NO_2) (where L = NO, NH_3, Py and 1-MeIm). For the first two, the metastable nitrito complexes Fe(Por)(NO)(ONO) and Fe(Por)(NH_3)(ONO) were also prepared at low temperatures. These isomerized to the more stable nitro form upon warming. All of the six-coordinate nitro- or nitrito complexes are low-spin.
(3) Reaction of NO_2 with Fe(Por)(ONO) leads to formation of five-coordinate bidentate nitrato complexes Fe(Por)(η^2-O_2NO) and evolution of NO. Less stable six-coordinate nitrato complexes of Fe(Por) with *trans* NO and tetrahydrofuran (THF) ligands have been spectroscopically characterized. Coordination of the 6th ligand is accompanied with monodentate–bidentate isomerization of coordinate nitrato ligand.
(4) In the presence of excess NO the nitrato complex Fe(TPP)(η^2-O_2NO) undergoes a series of transformations that result in formation of iron-porphyrin complexes ligated by the various nitrogen oxides The eventual products of solid state reactions are the nitrosyl complex Fe(TPP)(NO), the nitro-nitrosyl complex Fe(TPP)(NO_2)(NO) and the nitrato complex Fe(TPP)(η^2-O_2NO), the relative quantities of which are the function of NO partial pressure. Using low temperatures and labeled nitrogen oxides the mechanisms of these transformations have been elucidated. Notably a key step in these ready transformations is the formation of the strong oxidizing and nitrating agent nitrogen dioxide from nitrate ion and NO mediated by the presence of ferric heme models.

Acknowledgments

Financial support of ISTC (Project # A-484) is greatly acknowledged. PCF also thanks the US Department of Energy (DE-FG02-04ER15506) and the US National Science Foundation (CHE-0352650) for support.

References

[1] T.S. Kurtikyan, A.V. Gasparyan, G.G. Martirosyan, G.A. Zhamkochyan, J. Appl. Spectrosc. 62 (62) (1995) (Russ.).
[2] M. Kozuka, K. Nakamoto, J. Am. Chem. Soc. 103 (1981) 2162.
[3] K. Nakamoto, T. Watanabe, T. Ama, M.W. Urban, J. Am. Chem. Soc. 104 (1982) 3744.
[4] M.W. Urban, K. Nakamoto, F. Basolo, Inorg. Chem. 21 (1982) 3404.
[5] M.P. Byrn, C.J. Curtis, Y. Hsiou, S.I. Khan, P.A. Sawin, S.K. Tendick, A. Terzis, C.E. Strouse, J. Am. Chem. Soc. 115 (1993) 9480.
[6] T.S. Kurtikyan, G.G. Martirosyan, I.M. Lorkovic', P.C. Ford, J. Am. Chem. Soc. 124 (2002) 10124.
[7] H. Oshio, T. Ama, T. Watanabe, J. Kincaid, K. Nakamoto, Spectrochim. Acta 40A (1984) 863.
[8] L. Ignarro, Nitric Oxide: Biology and Pathobiology, Academic Press, San Diego, 2000.
[9] M. Hoshino, L. Laverman, P.C. Ford, Coord. Chem. Rev. 187 (1999) 75.
[10] L. Cheng, G.B. Richter-Addo, Porphyrin Handbook 4 (2000) 219.
[11] M.G. Espey, K.M. Miranda, M. Feelisch, J. Fukuto, M.B. Grisham, M. Vitek, D.A. Wink, Ann. N. Y. Acad. Sci. 899 (2000) 209.
[12] R. Radi, Proc. Natl. Acad. Sci. U.S.A. 101 (2004) 4003.
[13] X. Liu, M.J.S. Miller, M.S. Joshi, D.D. Thomas, J.R. Lancaster Jr., Proc. Natl. Acad. Sci. U.S.A. 95 (1998) 2175.
[14] P.C. Ford, D.A. Wink, D.M. Stanbury, FEBS Lett. 326 (1-3) (1993), and references therein.
[15] S. Pfeiffer, B. Mayer, B. Hemmens, Angew. Chem. Int. Ed. 38 (1999) 1714.
[16] J.O. Lundberg, M. Govoni, Free Radic. Biol. Med. 37 (2004) 395.
[17] M. Kirsch, H.-G. Korth, R. Sustmann, H. de Groot, Biol. Chem. 383 (2002) 389.
[18] N.S. Bryan, T. Rassaf, R.E. Maloney, C.M. Rodriguez, F. Saijo, J.R. Rodriguez, M. Feelisch, Proc. Natl. Acad. Sci. U.S.A. 101 (2004) 4308.
[19] K. Cosby, K.S. Partovi, J.H. Crawford, R.P. Patel, C.D. Reiter, S. Martyr, B.K. Yang, M.A. Waclawiw, G. Zalos, X. Xu, K.T. Huang, H. Shields, D.B. Kim-Shapiro, A.N. Schechter, R.O. Cannon, M.T. Gladwin, Nat. Med. 9 (2003) 1498.
[20] L. Knobeloch, B. Salna, A. Hogan, J. Postle, H. Anderson, Environ. Health Perspect. 108 (2000) 675.
[21] H. Bjoerne, M. Govoni, D.C. Toernberg, J.O. Lundberg, E. Weitzberg, Crit. Care Med. 33 (2005) 1722.
[22] T.S. Kurtikyan, G.M. Gulyan, G.G. Martirosyan, M.D. Lim, P.C. Ford, J. Am. Chem. Soc. 127 (2005) 6216.
[23] B.S. Tovrog, F.M. Mares, S.E. Diamond, J. Am. Chem. Soc. 102 (1980) 6616.
[24] J.A. Goodwin, R. Bailey, W.T. Pennington, R. Rasberry, T. Green, S. Shasho, M. Vongsavanh, E. Echevarria, J. Tiedeken, C. Brown, G. Fromm, S. Lyerly, N. Watson, A. Long, N. De Nitto, Inorg. Chem. 40 (2001) 4217.
[25] J.A. Goodwin, T.S. Kurtikyan, B.B. Zheng, D. Parmley, J. Howard, S. Green, R. Walsh, J. Standard, A.N. Mardyukov, D. Przybyla, Inorg. Chem. 44 (2005) 2215.
[26] T. Yoshimura, Inorg. Chim. Acta 83 (1984) 17.
[27] R. Lin, P. Farmer, J. Am. Chem. Soc. 123 (2001) 1143.
[28] G.R.A. Wyllie, W.R. Scheidt, Chem. Rev. 102 (2002) 1067.
[29] K.M. Miranda, X. Bu, I.M. Lorkovic, P.C. Ford, Inorg. Chem. 36 (1997) 4838.
[30] K.M. Kadish, V.A. Adamian, E.V. Caemelbecke, Z. Tan, P. Tagliatesta, P. Bianco, T. Boschi, G.-B. Yi, M.A. Khan, G.B. Richter-Addo, Inorg. Chem. 35 (1996) 1343.
[31] D.S. Bohle, P.A. Goodson, B.D. Smith, Polyhedron 15 (1996) 3147.
[32] I.M. Lorkovic', P.C. Ford, Inorg. Chem. 38 (1999) 1467.
[33] M.D. Lim, I.M. Lorkovic, P.C. Ford, Methods Enzymol. 396 (2005) 3, Part E.
[34] I.M. Lorkovic', P.C. Ford, Inorg. Chem. 39 (2000) 632.
[35] I.M. Lorkovic', P.C. Ford, J. Am. Chem. Soc. 122 (2000) 6516.
[36] J.C. Patterson, I.M. Lorkovic', P.C. Ford, Inorg. Chem. 42 (2003) 4902.
[37] J. Conradie, T. Wondimagegn, A. Ghosh, J. Am. Chem. Soc. 125 (2003) 4968.

[38] G.G. Martirosyan, A.S. Azizyan, T.S. Kurtikyan, P.C. Ford, Inorg. Chem. 45 (2006) 4079.
[39] G.G. Martirosyan, A.S. Azizyan, T.S. Kurtikyan, P.C. Ford, Chem. Commun. (2004) 1488.
[40] M.T. Gladwin, A.N. Schechter, D.B. Kim-Shapiro, R.P. Patel, N. Hogg, S. Shiva, R.O. Cannon III, M. Kelm, D.A. Wink, M.J. Espey, E.H. Oldfield, R.M. Pluta, B.A. Freeman, J.R. Lancaster Jr., M. Feelish, J.O. Lundberg, Nat. Chem. Biol. 1 (2005) 308, and references therein.
[41] M. Angelo, D.J. Singel, J.S. Stamler, Proc. Natl. Acad. Sci. U.S.A. 103 (2006) 8366.
[42] M.A. Hitchman, G.L. Rowbottom, Coord. Chem. Rev. 42 (1982) 55.
[43] O. Einsle, A. Messerschmidt, R. Huber, P.M.J. Kroneck, F. Neese, J. Am. Chem. Soc. 124 (2002) 11737.
[44] P.A. Williams, V. Fulop, E.F. Garman, N.F.W. Saunders, F.G. Ferguson, J. Hajdu, Nature 389 (1997) 406.
[45] B.R. Crane, L.M. Siegel, E.D. Getzoff, Biochemistry 36 (1997) 12120.
[46] H. Nasri, M.K. Ellison, S. Chen, B.H. Huynh, W.R. Scheidt, J. Am. Chem. Soc. 119 (1997) 6274.
[47] L. Cheng, D.R. Powell, M.A. Khan, G.B. Richter-Addo, Chem. Commun. (2000) 2301.
[48] J. Conradie, A. Ghosh, Inorg. Chem. 45 (2006) 4902.
[49] J. Lee, A.Y. Kovalevsky, I. Novozhilova, K. Bagley, P. Coppens, G.B. Richter-Addo, J. Am. Chem. Soc. 126 (2004) 7180.
[50] I.V. Novozhilova, P. Coppens, J. Lee, G.B. Richter-Addo, K.A. Bagley, J. Am. Chem. Soc. 128 (2006) 2093.
[51] D.M. Copeland, A.S. Soares, A.H. West, G.B. Richter-Addo, J. Inorg. Biochem. 100 (2006) 1413.
[52] T.S. Kurtikyan, P.C. Ford, Angew. Chem. Int. Ed. 45 (2006) 492.
[53] M.D. Lim, I.M. Lorković, K. Wedeking, A.W. Zanella, C.F. Works, S.M. Massick, P.C. Ford, J. Am. Chem. Soc. 124 (2002) 9737.
[54] T.S. Kurtikyan, A.A. Hovhannisyan, M.E. Hakobyan, J.C. Patterson, A. Iretskii, P.C. Ford, J. Am. Chem. Soc. 129 (2007) 3576.
[55] T.S. Kurtikyan, A.A. Hovhannisyan, G.M. Gulyan, P.C. Ford, Inorg. Chem. 46 (2007) 7024.
[56] M.G. Finnegan, A.G. Lappin, W.R. Scheidt, Inorg. Chem. 29 (1990) 181.
[57] R. Nasri, J.A. Goodwin, W.R. Scheidt, Inorg. Chem. 29 (1990) 185.
[58] H. Nasri, Y. Wang, B.H. Huynh, F.A. Walker, W.R. Scheidt, Inorg. Chem. 30 (1991) 1483.
[59] H. Nasri, K.J. Haller, Y. Wang, B.H. Huynh, W.R. Scheidt, Inorg. Chem. 31 (1992) 3459.
[60] T.S. Kurtikyan, T.G. Stepanyan, A.V. Gasparyan, Russ. J. Coord. Chem. 23 (1997) 563.
[61] T.G. Stepanyan, M.E. Akopyan, T.S. Kurtikyan, Russ. J. Coord. Chem. 26 (2000) 425.
[62] M.G. Elliot, R.E. Shepherd, Inorg. Chem. 26 (1987) 2067.
[63] J.C. Patterson, Ph.D. Dissertation, University of California, Santa Barbara, 2004.
[64] T.S. Kurtikyan, T.G. Stepanyan, M.E. Akopyan, Russ. J. Coord. Chem. 25 (1999) 721.
[65] T.S. Kurtikyan, T.G. Stepanyan, G.G. Martirosyan, R.K. Kazaryan, V.N. Madakyan, Russ. J. Coord. Chem. 26 (2000) 345.
[66] T.S. Kurtikyan, T.G. Stepanyan, Russ. Chem. Bull. 47 (1998) 695.
[67] S.K. O'Shea, W. Wang, R.S. Wade, C.E. Castro, J. Org. Chem. 61 (1996) 6388.
[68] T.S. Kurtikyan, J.S. Ogden, R.K. Kazaryan, V.N. Madakyan, J. Porphyrins Phthalocyanines 7 (2003) 623.
[69] Y. Kang, G.V. Zyryanov, D.M. Rudkevich, Chem. Commun. (2003) 2470.
[70] A.B.P. Lever, E. Mantovani, B.S. Ramaswamy, Can. J. Chem. 49 (1971) 1957.
[71] M.A. Phillippi, N. Baenziger, H.M. Goff, Inorg. Chem. 20 (1981) 3904.
[72] M.K. Ellison, M. Shang, J. Kim, W.R. Scheidt, Acta Crystallogr. Sec. C C52 (1996) 3040.
[73] T.S. Kurtikyan, G.G. Martirosyan, M.E. Hakobyan, P.C. Ford, Chem. Commun. (2003) 1706.
[74] G.M. Gulyan, T.S. Kurtikyan, P.C. Ford, submitted for publication.
[75] K. Tsuge, F. DeRosa, M.D. Lim, P.C. Ford, J. Am. Chem. Soc. 126 (2004) 6564.