

Formation of a Sulfur-Atom-Inserted N-Confused Porphyrin Iron Nitrosyl Complex by Denitrosation and C–S Bond Cleavage of an S-Nitrosothiol

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The reaction of nitrosothiol, Ph_3CSNO , with a divalent iron N-confused porphyrin complex, $\text{Fe}(\text{HCTPPH})\text{Br}$, yields a $\{\text{Fe}(\text{NO})\}_6^6$ iron nitrosyl complex with a sulfur atom inserted in the Fe–C bond. The crystal structure reveals a bent Fe–N–O geometry and an $\eta^2\text{-(C,S)}$ bonding mode between iron and the C–S bond. A reaction mechanism involving a transnitrosation and a nitrosothiol C–S bond cleavage is proposed.

The potential of using N-confused tetraphenylporphyrin (CTPP)^{1,2} complexes as heme model compounds has been mentioned in a recent paper,³ but only limited chemistry has been explored so far. A prerequisite for this would be the synthesis and characterization of a variety of biomolecule-related CTPP complexes. The coordination of nitric oxide, a well-known signaling molecule in biological systems,⁴ to a heme center of metalloproteins is known to be a dynamic pathway for signal transduction^{5,6} and NO delivery.^{7,8} One of the focuses on nitric oxide chemistry in recent years has been the understanding of NO delivery and storage. Recent results suggest that S-nitrosothiols can behave as NO transportation molecules and protein-bound or small-molecule nitrosothiols might play important roles in NO stasis and storage.^{9,10} As a model for NO transfer

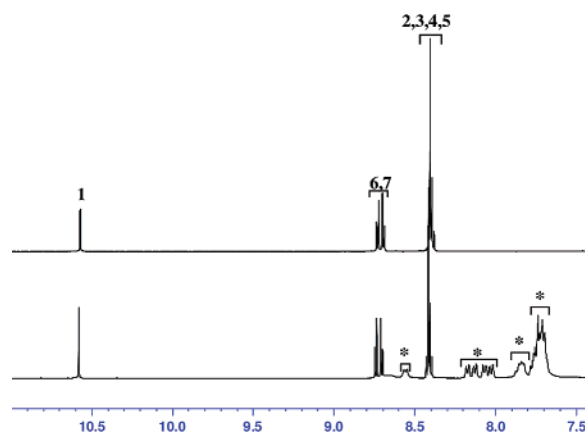


Figure 1. ^1H NMR spectra of $[\text{Fe}(\text{CTPPS})\text{NO}]$ (lower) and $[\text{Fe}(\text{CTPPS-}d_{20})\text{NO}]$ (upper). The asterisks mark the resonances from protons on meso-phenyl rings, and the numbers refer to β -pyrrolic protons on the carbon atoms labeled in Scheme 1.

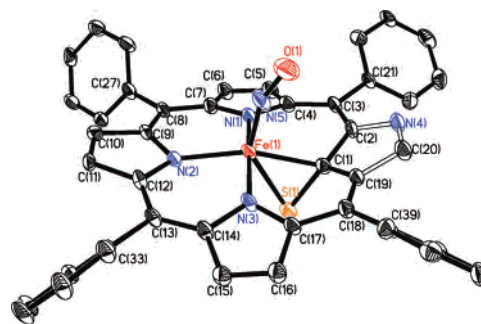


Figure 2. Molecular structure of **2** in 35% ellipsoids.

from a nitrosothiol to a metalloporphyrin, herein we report the reaction of S-nitrosotriphenylmethanethiol with an iron(II) N-confused porphyrin complex, as shown in Scheme 1.

Treatment of $[\text{Fe}^{\text{II}}(\text{HCTPPH})\text{Br}]^{11,12}$ (**1**) with 2 equiv of the S-nitrosothiol, Ph_3CSNO ,¹³ in dichloromethane shielded from light under anaerobic conditions at room temperature resulted in an instant change in its absorption spectrum. The progress of the reaction was monitored by UV–vis spectroscopy, and the final product had a broad Soret-like band at 433 nm and Q-band-type absorption at 570, 650, and 705 nm. The broadened and blue-shifted absorption spectrum

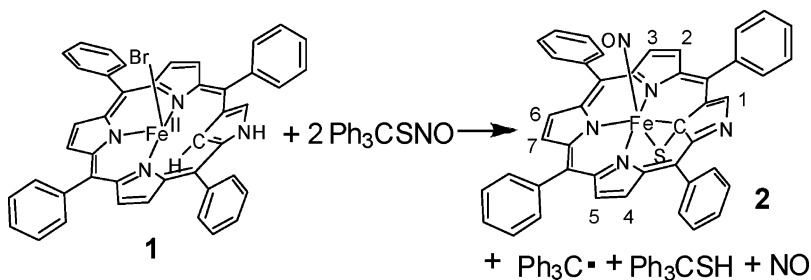
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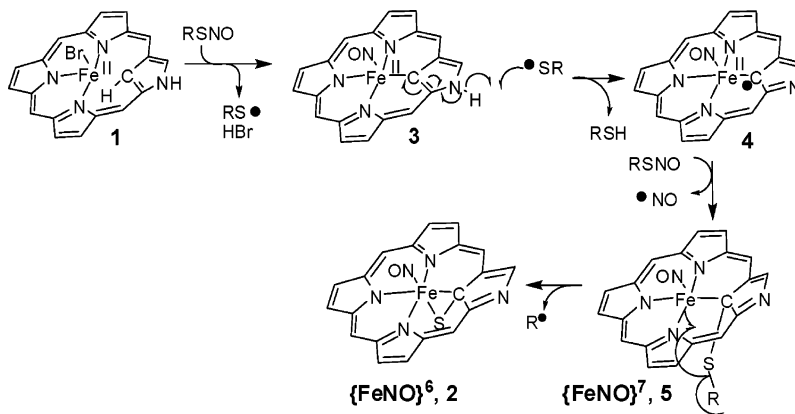
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Scheme 1



Scheme 2



resembled that of previously reported oxygen-inserted Fe-(HCTPPO)Br.¹⁴ The lack of an isosbestic point when monitoring the absorption changes suggested the existence of reaction intermediates contributing to the UV–vis spectra during progress of the reaction. A mass peak of the reaction product with m/z 700.42 in the electrospray ionization mass spectrometry spectrum matching the value for protonated [Fe-(CTPPS)], together with other spectroscopic characterizations and the X-ray single-crystal determination (vide infra), confirmed the formation of Fe(CTPPS)NO (**2**) as the final product.

Various spectroscopic methods provided important insights into the electronic structure of **2**. An intense $\nu(\text{NO})$ stretching frequency was located at 1775 cm^{-1} in the IR spectrum, which is in the energy range of a $\{\text{Fe}(\text{NO})\}^6$ electronic structure.^{15,16} The lack of an electron paramagnetic resonance (EPR) signal is also in agreement with a low-spin $\{\text{Fe}(\text{NO})\}^6$. As shown in Figure 1, in the ^1H NMR spectra, the chemical shifts of the six β -pyrrole protons, located between 8.41 and 8.74 ppm, are consistent with the diamagnetic characteristic for $\{\text{Fe}(\text{NO})\}^6$ complexes. The proton on the peripheral carbon of the inverted pyrrole ring was shifted to 10.58 ppm,

possibly because of the neighboring electronegative nitrogen atom. The ^{15}N NMR spectrum of the isotope-enriched [Fe-(CTPPS)¹⁵NO] gave a chemical shift of 8.19 ppm referenced to nitromethane. This chemical shift suggested a nitrosonium-type NO, and the electronic structure of the iron nitrosyl moiety can be considered to be $\text{Fe}^{2+}-\text{NO}^+$ in the solution state.¹⁷

The structure of single crystals obtained from vapor diffusion of *n*-hexane into **2** in toluene provided unambiguous assignment of the identity of the complex. The crystal structure reveals that the molecule (in Figure 2) consists of a nonplanar iron N-confused porphyrin with a bent nitric oxide as an axial ligand. A heavier sulfur atom underneath the Fe–C bond can be clearly identified from the electron density map. In the crystal lattice, back-to-back porphyrin orientation with a close-contact distance of $3.325(4) \text{ \AA}$ from the sulfur atom to a pyrrolic nitrogen atom was observed. Inside the porphyrin core, the inverted pyrrole ring tilts away from the porphyrin plane to give a twisting angle of $30.12(14)^\circ$ from the mean plane defined by 17 atoms on the tripyrrin unit. Although the spectroscopic data suggest a $\{\text{Fe}(\text{NO})\}^6$ electronic structure, the solid-state structure shows a Fe–N–O angle of $157.4(5)^\circ$ and reveals a bent nitrosyl coordination mode, which is distinctively different from the linear coordination mode in most $\{\text{Fe}(\text{NO})\}^6$ iron porphyrin complexes.¹⁶ Nevertheless, the angle is still larger than an average of 144.4° for five-coordinated $\{\text{Fe}(\text{NO})\}^7$ iron porphyrin nitrosyl complexes.¹⁸ A bent Fe–N–O structure with an angle of $157.4(2)^\circ$ has been observed in a $\{\text{Fe}(\text{NO})\}^6$

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(12) Symbol: CTPP is used to denote the N-confused tetraphenylporphyrin ring. The group attached to the peripheral nitrogen atom will be indicated by a prefix in *italic*, and the group attached to the inner carbon atom will appear as a suffix in *italic*. Abbreviation: OEP, dianion of octaethylporphyrin; TpivotPP, dianion of (tetrapivalamido)-phenylporphyrin.

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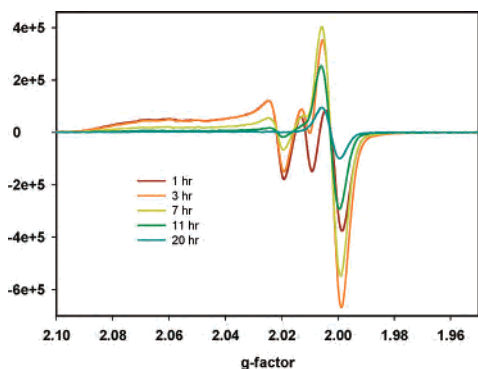


Figure 3. EPR spectra of reaction aliquots recorded at 77 K taken during the reaction of **1** with Ph_3CSNO .

metalloporphyrin, $[\text{Fe}(\text{OEP})(p\text{-C}_6\text{H}_4\text{F})(\text{NO})]$,¹⁹ and the bending has been attributed to the presence of a strong σ -donating phenyl group in the position trans to nitric oxide. The observation of bent Fe–N–O in **2** suggests that significant electron density can be provided from the coordinating CS^- unit back-donating to the nitric oxide. Furthermore, the distance of 1.666(5) Å for the Fe–N bond between iron and nitric oxide is much shorter than the 1.753 Å in $\{\text{Fe}(\text{NO})\}^7$ iron porphyrin complexes¹⁸ and is close to 1.668(2) Å found in $\{\text{Fe}(\text{NO})\}^6$ $[\text{Fe}(\text{TpivPP})(\text{NO})(\text{NO}_2)]$. Like other NO complexes, the axial Fe–N vector exhibits a 5.88° deviation from the normal of the 17-atom tripyrrole mean plane leaning toward the inverted pyrrole ring. The projection of the NO onto the porphyrin plane eclipses with the Fe–C vector.

Insertion of an oxo or nitrene group into the Fe–N bond on iron porphyrin complexes is well documented.^{20–22} The reactive Fe–C bond inside the iron N-confused porphyrin has been known to activate dioxygen, and an oxo group can be inserted into the Fe–C bond.¹⁴ However, the insertion of a sulfur atom to form the Fe(CTPPS) porphyrin core is unprecedented in porphyrin chemistry. On the inverted pyrrole ring, the internal C–C single bonds, C(1)–C(2) and C(1)–C(19), with distances of 1.493(7) and 1.444(7) Å, respectively, are much longer than the corresponding distances, 1.391(14) and 1.399(15) Å, in the starting **1**.¹¹ The C–S bond distance of 1.763(5) Å is close to the C–S single bond value.²³ The distances of 2.051(6) and 2.2432(17) Å from iron to inner carbon and sulfur, respectively, fall within the normal range for coordination bonds. In short, the distances and conformation surrounding iron and the inverted pyrrole ring suggest that the C–S bond in the pyrrolyl sulfide moiety coordinates to the iron center in a $\eta^2(\text{C},\text{S})$ bonding mode to give a metallocyclopropane-type three-membered ring. The inner carbon, C(1), exhibits a pseudotetrahedron geometry, with the plane of the inverted pyrrole ring bisecting the Fe–C–S angle.

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The nitrosation of a metalloporphyrin by an *S*-nitrosothiol can go through either homolytic or heterolytic pathways.^{9,24,25} When the reaction of **1** is monitored with Ph_3CSNO by EPR spectroscopy, as shown in Figure 3, a $\{\text{Fe}(\text{NO})\}^7$ signal at $g = 2.02$ and $a_{\text{N}} = 1.66$ mT rapidly appeared, reached its maximum in the first hour, and then decayed slowly in concert with the increase of a free-radical signal. The final reaction mixture gave only the free-radical signal without the presence of a residual three-line signal. The observation of a three-line-pattern EPR signal, a characteristic pattern for $\{\text{Fe}(\text{NO})\}^7$ species,^{26,27} as a reaction intermediate as well as the presence of a radical signal at $g = 2.002$ suggests that homolytic cleavage of the S–NO bond in Ph_3CSNO is more likely. A plausible mechanism for the reaction of Ph_3CSNO with **1**, consistent with the EPR, mass, and NMR spectroscopy measurements, is postulated in Scheme 2. The coordination of NO and elimination of HBr give a $\{\text{Fe}(\text{NO})\}^7$ complex **3** and a $\text{Ph}_3\text{CS}^{\bullet}$ radical. The radical reacts on the CTPP core to form a CTPP cation radical **4**, which couples with another 1 equiv of $\text{Ph}_3\text{CS}^{\bullet}$ to give compound **5**. The formation of the Fe–S bond completes the reaction and releases the $\text{Ph}_3\text{C}^{\bullet}$ radical. The observation of mainly nitrosation product, **3** or **4**, in mass spectra in the early stage of the reaction suggests that nitrosation occurs before the $\text{Ph}_3\text{CS}^{\bullet}$ radical attacks the porphyrin ring. The formation of Ph_3CSH was confirmed by NMR, while $\text{Ph}_3\text{C}^{\bullet}$ was recovered as $[(\text{Ph}_3\text{C})\text{O}]_2$ during column chromatography under aerobic conditions and confirmed by X-ray structure determination (see the Supporting Information).

In summary, the reaction of **1** with Ph_3CSNO demonstrates unusual bond-breaking and bond-formation reactions in an iron N-confused porphyrin complex. The observation of a bent Fe–NO is rare for an iron porphyrin complex with an $\{\text{Fe}(\text{NO})\}^6$ electronic structure. Considering the ubiquitous roles of nitrosothiols in biological systems, the potential application of this chemistry is intriguing. Reactions using *S*-nitrosothiols with a variety of substituents to understand the generality and reaction rate of NO transfer are currently under active investigation in our laboratory.

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Supporting Information Available: Experimental details, IR, NMR, and mass spectra of **2**, and crystallographic data of **2**. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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