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Short Communication

When being straight bends rules: A rationale for the linear FeNO unit in the low-spin square-pyramidal $\{FeNO\}^7$ tetracyanonitrosylferrate(2−) anion

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Abstract

All low-spin $S = 1/2$ heme–NO complexes feature FeNO angles of about 140°. In contrast, the square–pyramidal $[Fe(CN)_4(NO)]^{2-}$ complex features an exactly linear $\{FeNO\}^7$ unit. We have sought here to determine a possible, simple molecular orbital (MO) rationale for these structural variations. A DFT-based (DFT = density functional theory) MO analysis shows that the linearity of the latter stems from the greater pyramidalization of the Fe center, relative to nitrosylheme, which results in significant differences in d orbital hybridization. Thus, the singly occupied molecular orbital (SOMO) of $[Fe(CN)_4(NO)]^{2-}$, while primarily Fe d_{z^2}-based, also has a significant amount of $4p_z$ character, which makes it less stereochemically active, accounting for the linearity of the FeNO unit.

Keywords: Tetracyanonitrosylferrate; NO donor; Nitroprusside

Transition metal–NO complexes [1–4] are currently attracting considerable interest as biomedical NO delivery agents [5,6]. Sodium nitroprusside, $Na_2[Fe(CN)_5(NO)]\cdot 2H_2O$, is the gold standard of such NO donors, having been in use for over 75 years, most commonly for hypotensive anesthesia during surgery [7,8]. The nitroprusside anion, an $\{FeNO\}^6$ species, is reduced *in vivo* by thiolates and other reductants, yielding an equilibrium mixture of the following $\{FeNO\}^7$ anions [9], the second of which is the subject of this DFT study:

$$[Fe(CN)_5(NO)]^{3-} = [Fe(CN)_4(NO)]^{2-} + CN^-$$

Traditionally (see e.g. [10] and references therein), the tetracyanonitrosylferrate(2−) anion has been viewed as labile toward NO dissociation and hence ultimately responsible for the rapid vasodilatory action of nitroprusside. However, based on a detailed kinetics analysis, van Eldik and coworkers have argued against this proposal, suggesting instead that the $[Fe(CN)_3(NO)]^-$ anion may be one of the actual fast NO-releasing intermediates involved in nitroprusside treatment [9]. Recently, the red and black Roussin's salts and their esters have been investigated as photochemical NO delivery agents [11]. The advantage of the photochemical approach is that it enables targeted NO delivery to specific locations, for instance, to bring about NO-induced cell death in the course of photodynamic therapy of a localized cancer [12,13]. Thus, a variety of photolabile metal nitrosyls have been reported in recent months and years [14,15] of which a particularly good example, from a biomedical NO delivery point of view, is a polyurethane-coated sol-gel material containing a photoactive $\{MnNO\}^6$ complex which rapidly releases NO with high quantum efficiency when exposed to visible light of low intensity [16].

We have recently carried out a relatively broad density functional theory (DFT) survey [17] of metalloporphyrin–NO complexes [18] and have initiated a similar survey of

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nonheme NO complexes. Our hope is that a better appreciation of the electronic structures of the latter complexes will lead to a more rational approach toward developing new NO donor drugs. As an early step in that direction, we present here a DFT study of the $[Fe(CN)_4(NO)]^{2-}$ anion [19,20]. The FeNO unit in this $S = 1/2$ $\{FeNO\}^7$ species might have been expected to be bent, according to the rules of thumb [1,17,18] applicable to metalloporphyrin–NO complexes, but it is not; the $[Fe(CN)_4(NO)]^{2-}$ ion exhibits exact C_{4v} symmetry. The thumb rules in question are as follows. The MNO angle in metalloporphyrin–NO complexes depends sensitively on the Enemark–Feltham electron count [1], which is the number of d electrons plus NO π^* electrons. Thus, $\{MNO\}^6$ porphyrins, which are invariably low-spin $S = 0$ species, generally exhibit linear MNO units, which maximizes $M(d_\pi)$–$NO(p_\pi)$ π-bonding [21]. However, $\{MNO\}^7$ porphyrins invariably feature a strongly bent MNO unit with an MNO angle of about 140°, reflecting the shape of the singly occupied molecular orbital (MO), which involves a σ-bonding interaction of the metal d_{z^2} orbital and an NO π^* orbital [22,23]. Fig. 1 depicts this MO for nitrosylheme, the paradigmatic low-spin $\{MNO\}^7$ complex. In the same vein, $\{MNO\}^8$ units in porphyrins (e.g. $\{CoNO\}^8$ porphyrins [24]) are even more bent, with a typical MNO angle of about 120°. However, exceptions to these rules of thumb are slowly accumulating, underscoring the remarkable malleability of metal–NO bonding. As discussed below, a number of $\{MNO\}^6$ porphyrins with bent MNO units have recently been reported. The tetracyanonitrosylferrate(2−) anion [5,6] is another exceptional species, a low-spin square–pyramidal $\{FeNO\}^7$ complex with a linear FeNO unit. Can we explain this structure in terms of a simple MO argument?

To gain insight into this question, we carried out DFT optimizations (using the ADF program system [25]) of $[Fe(CN)_4(NO)]^{2-}$ with the PW91 [26] and OLYP [27] generalized gradient approximation (GGA) functionals and a variety of different symmetry constraints. A C_{4v} symmetry constraint forced a square–pyramidal (SP) geometry. A C_{3v} constraint resulted in a trigonal bipyramidal (TBP) geometry with an apical NO, while a TBP geometry with an equatorial NO could be explored using a C_{2v} symmetry constraint. In addition, fully unconstrained optimizations were also carried out. Both the C_{2v} and C_1 optimizations led to structures indistinguishable from the C_{4v} optimized geometry, which turns out to be the sole minimum on the ground state potential energy surface. Fig. 2 depicts key optimized geometry parameters and the spin density profiles obtained with the two functionals for the C_{4v} minimum. We also examined the $S = 3/2$ state for a variety of stereochemistries. The lowest-energy $S = 3/2$ state was calculated to be 1.62 and 1.26 eV above the $S = 1/2$ ground state for the PW91 and OLYP functionals, respectively; given these high energies, we will not discuss the $S = 3/2$ any further in this report.

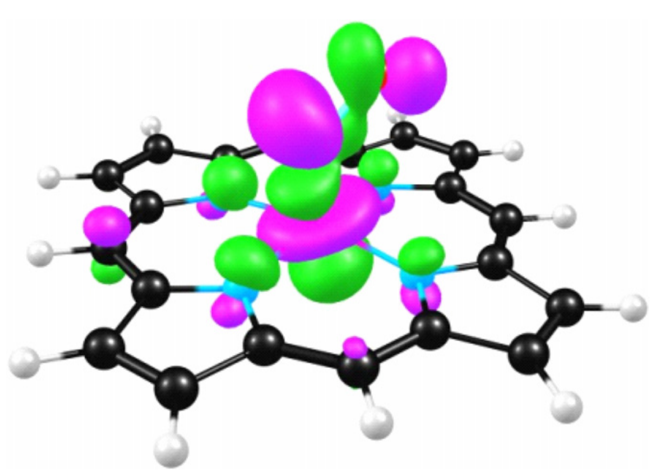

Fig. 1. The majority-spin HOMO (SOMO) of Fe(P)(NO): 54.5% Fe d, 3.3% Fe p, 14.7% N(NO), 8.7% O.

The TBP geometry with an apical NO is quite high in energy, 0.78 eV above the C_{4v} minimum, for both the PW91 and OLYP functionals. Fig. 3 presents comparative MO energy level diagrams for the C_{4v} and C_{3v} structures. In essence, the instability of the C_{3v} conformation results from metal–ligand antibonding σ-interactions in the *xy*-plane (the C_3 axis being identified with the *z*-axis). Incidentally, we [28] noted a similar instability of a TBP conformation with an apical NO on a previous occasion, for a simple model of Fe(5,5-tropocoronand)(NO) [29].

As in the case of an earlier DFT study [30] (which, among other things, presented a TDDFT study of the electronic spectrum of $[Fe(CN)_4(NO)]^{2-}$, an aspect that we will not focus on in this study) our PW91 and OLYP optimized C_{4v} structures (Fig. 2) agree well with experiment [31] but are otherwise relatively unremarkable. (Mention might also be made of an early *ab initio* Hartree–Fock study on $[Fe(CN)_4(NO)]^{2-}$, which also predicted a C_{4v} structure [32].) However, note that the pyramidalization of the Fe center is considerably greater than that in Fe(P)(NO), which is not surprising given that unlike the four cyanides, a porphyrin is a sterically constrained cyclic ligand. Thus, the Fe is 0.452 Å above the cyanide C_4 plane in $[Fe(CN)_4(NO)]^{2-}$ while it is only 0.269 Å above the porphyrin N_4 plane in Fe(P)(NO) [23]. Another interesting observation from Fig. 2 concerns small but significant differences between the PW91 and OLYP spin density profiles. In particular, note the increased minority spin density on the NO in the OLYP spin density profile. The minority spin density on the NO may be viewed as a small amount of $Fe(S_1 = 3/2)$–$NO^-(S_2 = 1)$ character.

As in the case of Fe(P)(NO), the shape of the singly occupied MO, shown in Fig. 4, provides the key clue to the shape of the FeNO unit. While the Fe d_{z^2} orbital in Fe(P)(NO) looks like a normal d_{z^2} orbital, as shown in Fig. 1, the one in Fig. 4 does not. The lobe of the d_{z^2} orbital *trans* to the NO is decidedly swollen while the lobe on the same side as the NO is correspondingly shrunken. Stated differently, this MO, though primarily Fe d_{z^2}-based, also has a significant amount (about 12%) Fe $4p_z$ character. The shrunken lobe of the Fe "d_{z^2}" orbital on the NO side,