Synthetic Analogs for the MoFe₃S₃ Subunit of the Nitrogenase Cofactor: Structural Features Associated with the Total Number of Valence Electrons and the Possible Role of M–M and Multiple M–S Bonding in the Function of Nitrogenase

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The cofactor of nitrogenase[1] is supported by an octanuclear MoFe₇S₉ framework[1a,b,2] that appears to be stabilized by extensive Fe–Fe bonding. The most recent, high-resolution, crystallographic structure of nitrogenase reports Fe–Fe distances for the cofactor[1b] that range from 2.46(10) to 2.74(9) Å with a mean value of 2.56-(5) Å.[3a] This is somewhat shorter than that determined by Fe EXAFS analysis[3b–d] (2.63 Å) and significantly shorter (~0.1 Å) than the mean values of the Fe–Fe distances in the Fe₄S₄ ferredoxin cubane clusters and their synthetic analogues.[4] The structural data suggest that the apparent coordination unsaturation associated with the iron atoms within the prismatic Fe₆ central core is compensated by extensive Mo–Fe and Fe–Fe bonding. The profound structural changes that accompany the gain or loss of electrons by the octanuclear P-clusters of nitrogenase[1b,5] pose the question whether significant changes also occur in the FeMo cofactor of nitrogenase following electron transfer. Indeed, changes in Fe–Fe bonding, brought about by addition of electrons to this electron-deficient center, may be of crucial importance in the binding and activation of N₂.

The Fe₄S₃ and MoFe₃S₃ cuboidal cores found[1,2] as structural subunits in the nitrogenase FeMoS cofactor are not common in cluster chemistry. The former is present in the [Fe₄S₃(NO)₇]⁺, Roussin's black salt[6] and its PR₃ derivatives[7] while the latter was only recently found in the (Cl₄-cat)(O)MoFe₃S₃(CO)₅(PEt₃)₃ and (Cl₄-cat)MoFe₃S₃(CO)₆(PEt₃)₂ clusters[8] obtained in reactions of the [(Cl₄-cat)MoFe₃S₄(PEt₃)₃]₂ fused-double cubane,[9] (**I**), with carbon monoxide.

In this contribution we report the synthesis and structural characterization of new clusters that contain the MoFe₃S₃ cuboidal center and exhibit dramatic core structural changes associated with
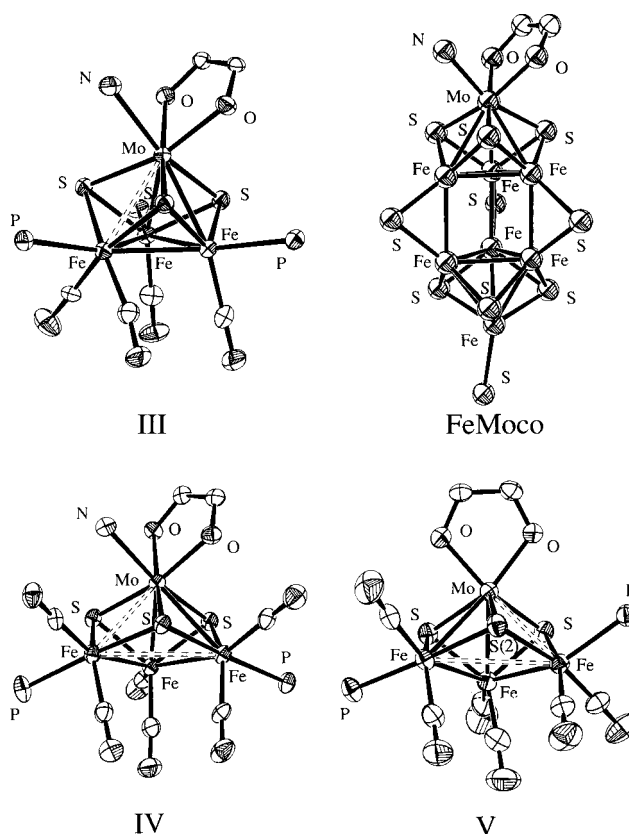

Figure 1. Structures of **III**, (Cl₄-cat)(Py)MoFe₃S₃(CO)₄(PⁿPr₃)₃, Fe–Fe, 2.592(7) Å, (range: 2.565(1)–2.609(1) Å), Mo–Fe, 2.73(5) Å, Fe–S, 2.23(1) Å, Mo–S, 2.332(2) Å; the FeMo cofactor of nitrogenase;[1d] **IV**, (Cl₄-cat)(Py)MoFe₃S₃(CO)₆(PEt₃)₂, Fe–Fe, 3.618(1) Å, 2.6776(9) Å, 2.703(1) Å, Mo–Fe, 2.76(5) Å, Fe–S 2.23(1) Å Mo–S, 2.31(2) Å; and **V**,[8a] (Cl₄-cat)MoFe₃S₃(CO)₆(PEt₃)₂, Mo–Fe, 2.680(1) Å, 2.776(1) Å, 2.849(1) Å, Fe–Fe, 2.625(1) Å, 2.702(1) Å, 2.635(1) Å. Fe–S, 2.24(2) Å (range: 2.174(1)–2.310(1) Å), Mo–S 2.214(1), 2.306(1) Å, 2.306(1) Å. For clarity the alkyl groups on the R₃P ligands are not included, only the pyridine (or histidine imidazole for the cofactor) N atoms are shown, and only the carbon atoms adjacent to the O donor atoms in the tetrachlorocatecholate ligands in **III**, **IV**, and **V** and the homocitrate ligand in the cofactor are drawn.

the ligand environment and the total number of valence electrons. The reaction of the [(Cl₄-cat)MoFe₃S₄(PⁿPr₃)₃]₂ fused-double cubane (**II**)[10] with CO at a pressure of 500 psi, in CH₂Cl₂ under a dinitrogen atmosphere saturated with pyridine, after 3 days yielded the (Cl₄-cat)(Py)MoFe₃S₃(CO)₄(PⁿPr₃)₃ cluster (**III**).[11,12] Under identical reaction conditions the reaction of **I** with CO yielded the (Cl₄-cat)(Py)MoFe₃S₃(CO)₆(PEt₃)₂ cluster (**IV**).[12,13] The clusters **III** and **IV** have been separated from reaction mixtures by column chromatography in yields of 9 and 25%, respectively. Both **III** and **IV** adopt a structure[14] (Figure 1) based on the corner-sulfide voided MoFe₃S₃, Roussin-like, cuboidal core. In **III**, two of the Fe atoms are four-coordinate each with a CO and a ⁿPr₃P as terminal ligands and the third is five-coordinate

(1) (a) Kim, J.; Rees, D. C. *Science* **1992**, *257*, 1677. (b) Peters, J. W.; Stowell, M. H. B.; Soltis, S. M.; Finnegan, M. G.; Johnson, M. K.; Rees, D. C. *Biochemistry* **1997**, *36*, 1181 and references therein.

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(3) (a) The standard deviation reported is from the mean of the 12 Fe–Fe distances reported for the cofactor[1d] (b) Harvey, I.; Strange, R. W.; Schneider, R.; Gormal, C. A.; Hasnain, S. S.; Richards, R. L.; Smith, B. E. *Inorg. Chim. Acta* **1998**, *276*, 150. (c) Christiansen, J.; Tittsworth, R. C.; Hales, B. J.; Cramer, S. P. *J. Am. Chem. Soc.* **1995**, *117*, 10017. (d) Liu, H. B. I.; Filiponi, A.; Gavini, N.; Burgess, B. K.; Hedman, B.; Dicicco, A.; Natoli, C. R.; Hodgson, K. O. *J. Am. Chem. Soc.* **1994**, *116*, 2418.

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(6) (a) Roussin, F. Z. *Ann Chim. Phys.* **1858**, *52*, 285. (b) Chu, C.-W.; Dahl, L. F. *Inorg. Chem.* **1977**, *16*, 3245.

(7) (a) Scott, M. J.; Holm, R. H. *Angew. Chem., Int. Ed. Engl.* **1993**, *32*, 564. (b) Goh, C.; Holm, R. H. *Inorg. Chim. Acta* **1998**, *270*, 46.

(8) (a) Tyson, M. A.; Coucouvanis, D. *Inorg. Chem.* **1997**, *36*, 3808. (b) Cl₄-cat = tetrachlorocatecholate dianion. (c) The structure of **V** has been further refined to an *R* value of 0.026. Excellent analytical data for **V** and **VI** have been reported previously.[8a]

(9) Demadis, K. D.; Campana, C. F.; Coucouvanis, D. *J. Am. Chem. Soc.* **1995**, *117*, 7832.

(10) This compound was obtained using a synthetic procedure analogous to that used in the synthesis of **I**. (See Supporting Information).

(11) For **III**, IR (KBr); CO region: 2021(vs), 1987(vs), 1974(m), 1958(s), 1928(s).

(12) Only poorly defined, irreversible voltammetric waves could be obtained between +1.5 and −1.5 V. This behavior is not surprising, considering the profound structural changes that accompany changes in the total electron count.

(13) For **IV**, IR (KBr); CO region: 2026(s), 2005(s), 1975(m), 1945(vs), 1891(m).

(14) Elemental analyses, spectroscopic data, and crystal data for compounds **III**, **IV**, and **VII** have been deposited as Supporting Information.

with two CO and one $^{n}Pr_3P$ ligands. The MoFe$_3$ unit adopts a butterfly arrangement, and the three Fe atoms define a nearly equilateral triangle with short Fe−Fe distances (Figure 1) that have a mean value of 2.592(7) Å. The "wing-tips" of the butterfly at a distance of 2.887(1) Å are occupied by the Mo and the five-coordinate Fe atoms. In **IV**, the three Fe atoms define an isosceles triangle also in a butterfly arrangement of the MoFe$_3$ unit (Figure 1). Two of these Fe atoms are five-coordinate with trigonal bipyramidal geometry, separated by 3.618(1) Å from each other and located at a distance of 2.6776(9) and 2.7030(10) Å, respectively, from the third Fe atom. The latter has a four-coordinate trigonal pyramidal structure.

The difference in the total valence electron count between these clusters (only two electrons) is reflected in a dramatic lengthening of one of the Fe–Fe bonds from ∼2.60 Å in **III** *(60 e^{-}) to ∼3.62 Å in* **IV** *(62 e^{-})!* The similarities of the *mean* Mo−Fe, Fe−S, and Mo−S distances in **III** and **IV** (Figure 1), suggest that addition of two electrons in **III** (by introducing one additional terminal ligand) affects the core and leads to **IV**, possibly with the population of an antibonding LUMO mainly of Fe character. The previously reported[8] (Cl$_4$-cat)MoFe$_3$S$_3$(CO)$_6$(PEt$_3$)$_2$,**V**, upon oxidation yields (Cl$_4$-cat)(O)MoFe$_3$S$_3$(CO)$_5$ (PEt$_3$)$_3$, **VI**,[8] and more recently the nearly isostructural (Cl$_4$-cat)(O)MoFe$_3$S$_3$(CO)$_6$-(PEt$_3$)$_2$,[12,15] **VII**. Both **VI** and **VII** are 66 e^{-} clusters[16] and each contains an oxo ligand bound to the Mo atoms (in place of the Py ligand in **IV**). In the structures of **VI** and **VII** (Mo=O, 1.625-(7) and 1.697(4) Å) the three Fe atoms define an isosceles triangles similar to that in **IV** (Figure 1). The mean Mo−Fe distances of 3.4(1) and 3.4(1) Å in **VI** and **VII**, respectively,[17] are longer than those in **III** (2.73(5) Å) and **IV** (2.76(5) Å) consistent with the additional electrons occupying an antibonding orbital with significant Mo and Fe character.

In **V** an isosceles triangle of Fe atoms is also present, and the mean values for the Fe−Fe and Mo−Fe distances (Figure 1) compare to corresponding distances in **IV** (62 e^{-}). The major structural difference between the cores of **V** and **IV** is a short Mo−S bond in **V**, where S(2) serves as an axial ligand for the square pyramidal Mo atom at 2.214(1) Å.[18] This bond is significantly shorter than those with the equatorially located S^{2-} ligands at 2.306(1) and 2.305(1) Å. The data suggest that, as a result of the Mo=S(2) bond, the μ_3-S(2)$^{2-}$ ligand serves as an

eight-electron donor in **V**, which consequently is best described as a 62-valence electron cluster.

An analysis of the structural features of the MoFe$_3$S$_3$ core in **III** and a comparison with the MoFe$_3$S$_3$ subunit in the nitrogenase cofactor shows (Figure 1) the two to be metrically quite similar with a CO ligand in two of the Fe atoms in **III** occupying the site of an intersubunit Fe−Fe bond in the FeMoco,[19] and an Fe−P^{n}Pr$_3$ bond for each of the Fe atoms in **III** corresponding to a μ_2−S bond in the FeMoco.[20]

The structure of the electron-deficient FeMoco is stabilized considerably by Fe−Fe bonding with each of the six central Fe atoms bound intra- and intersubunit to four other metals. An electron count, assuming the μ_3-S^{2-} and μ_2-S^{2-} ligands as six- and four-electron donors, respectively, shows that even with a full complement of M−M bonds the M atoms fall short of the effective number of electrons (18) considered important for stability. The presence of short M−S bonds in the cofactor (the limited accuracy of the crystallographic results notwithstanding) is evident in the mean value of the Fe−S (2.19(5) Å) and Mo−S (2.25(5) Å) bond lengths. It appears therefore that, in addition to M−M bonding, the donation of more electrons by the μ_3-S^{2-} and μ_2-S^{2-} ligands (multiple M−S bonding) in effect stabilize the structure of the cofactor. In the latter, *the ability of the bridging sulfido ligands to "shift" valence electrons into and out of the bonding scheme,[22] and the making and breaking of M−M bonds will facilitate the structural changes that very likely occur during the catalytic cycle.* Indeed, the elongation (breaking) of Fe−Fe bonds that may follow the reduction of the cofactor to the catalytically active redox level, could provide sites suitable for N$_2$ binding, activation, and reduction. The coupling of clusters such as **III** and **IV** and the synthesis of the next generation of analogues for the nitrogenase cofactor are presently under investigation.

Supporting Information Available: Detailed synthesis and characterization of the compounds. ORTEP plots of **III**, **IV** and **VII**. Tables S1, S2 and S3 containing listings of positional parameters, thermal parameters, selected distances and angles of **III**, **IV** and **VII** (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

JA991880O

(15) The synthesis of **VII** from **V** was accomplished by the addition of trimethylamine-*N*-oxide to a solution of **V** in toluene. IR ν-CO for **VII**: 2043-(vs), 2034(s), 2019(s), 2000(vs), 1980(s), 1968(s), 1943(m); *n*-Mo=O: 931-(m).

(16) The electron count for **VII** (and **VI**) considers the sulfide ligand *trans* to the Mo=O group as an eight-electron donor. This is based on this ligand, S(2), forming three "regular" bonds to the three Fe atoms (mean S(2)−Fe bond length, 2.300(8) Å) and a long bond to the Mo atom (2.637(2) Å).

(17) The individual Mo−Fe distances in **VII** are similar to those in **VI**.

(18) Coucouvanis, D. *Adv. Inorg. Chem.* **1998**, *45*, 1−73.

(19) One of the Fe atoms in **III** is coordinated by two carbonyl ligands.

(20) Recent spectroscopic studies of CO-derivatives of the FeMoco have been reported.[21]

(21) (a) George, S. J.; Ashby, G. A.; Wharton, C. W.; Thorneley, R. N. F. *J. Am. Chem. Soc.* **1997**, *119*, 6450. (b) Lee, H.-I.; Cameron, L. M.; Hales, B. J.; Hoffman, B. M. *J. Am. Chem. Soc.* **1997**, *119*, 10121.

(22) This is uniquely facilitated by covalency in the Mo−S bonds as a result of effective energy matching between the sulfur 3p and the Mo 4d atomic orbitals.[18]