NITROSYL COMPLEXES OF IRON–SULFUR CLUSTERS

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I. Introduction

The first iron–sulfur–nitrosyl complexes, in salts now known to contain the anions $[Fe_2S_2(NO)_4]^{2-}$ and $[Fe_4S_3(NO)_7]^-$, were described by Roussin in 1858 (*1*). Although Roussin did not know the precise compositions of the new salts, far less their constitutions, he was convinced of their close relationship to the nitroprusside anion $[Fe(CN)_5NO]^{2-}$, which had only recently been described by Playfair (*2*). The empirical formulas of a range of salts $M_2^I[Fe_2S_2(NO)_4]$ and $M^I[Fe_4S_3(NO)_7](M^I = Na, K, Tl, \text{or } NH_4)$ were determined by Pavel in 1882 (*3*) as a result of some painstaking elemental analyses. Pavel also prepared the first organic derivative $[Fe_2(SEt)_2(NO)_4]$ by alkylation, using $K_2[Fe_2S_2(NO)_4]$, and established its empirical formula. Subsequent molecular weight determinations on a range of organic derivatives, which had been prepared by reaction of thiols and iron(II) salts with nitric oxide (*4*), showed that these compounds had dimeric molecular formulas $[Fe_2(SR)_2(NO)_4]$. Subsequent work early in the present century confirmed the dimeric nature of $[Fe_2(SR)_2(NO)_4]$ (*5*), and demonstrated that both $[Fe_2(SR)_2(NO)_4]$ and salts containing $[Fe_2S_2(NO)_4]^{2-}$ or $[Fe_4S_3(NO)_7]^-$ are diamagnetic (*6*).

Based upon the molecular formulas, but upon no other evidence, a range of structural formulas were proposed (*5, 7–9*), including structures containing *cis*-hyponitrite ligands (*5*) and bridging NO groups (*9*). Definitive structural formulas were established only by the simultaneous publication in 1958, exactly 100 years after Roussin's original description of these complexes (*1*), of X-ray structure determinations for $[Fe_2(SEt)_2(NO)_4]$ (*10*) and $Cs[Fe_4S_3(NO)_7]\cdot H_2O$ (*11*).

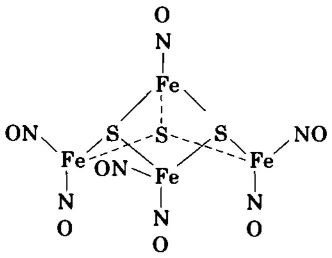
The recent upsurge of interest in iron–sulfur–nitrosyl complexes has been stimulated in part by the reported isolation of $[Fe_2(SMe)_2(NO)_4]$ from natural sources (*12*), by the obvious resemblances between these complexes and the naturally occurring [2Fe–2S] and [4Fe–4S] clusters of iron–sulfur proteins (*13, 14*), and by the connections between tetrairon–sulfur–nitrosyls and cubane-type clusters (*15*). Most of the work in this area has been published in the past 5 years or so, and no review has previously been made. However, a number of excellent reviews of the wider aspects of metal–nitrosyl chemistry have appeared (*16–19*).

Salts containing the anions $[Fe_2S_2(NO)_4]^{2-}$ and $[Fe_4S_3(NO)_7]^-$ are often called, from their colors, Roussin's red and black salts, respectively: similarly the organic derivatives $[Fe_2(SR)_2(NO)_4]$ are often called esters of Roussin's red salt. These names are nonsystematic and, in the case of $[Fe_2(SR)_2(NO)_4]$, scarcely accurate; nonetheless they are convenient and they carry the sanction of long usage, and will on occasion be used here.

II. Synthesis

A. $[Fe_4S_3(NO)_7]^-$ AND $[Fe_2S_2(NO)_4]^{2-}$

Salts containing these two anions, structures **1** and **2**, were obtained in impure form by Roussin in 1858 (*1*): the anion $[Fe_4S_3(NO)_7]^-$ is conveniently synthesized using a modification (*20*) of Roussin's method.



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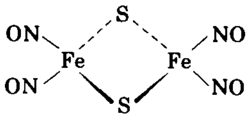

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Reaction of iron(II) sulfate with a mixture of sodium nitrite and ammonium sulfide yields an intensely black solution from which $NH_4[Fe_4S_3(NO)_7]$ can be crystallized: alternatively, since salts of $[Fe_4S_3(NO)_7]^-$ are all soluble in diethyl ether, the crude reaction mixture can be extracted with ether to yield the product. Other salts can readily be prepared by metathesis.

The conversion of $[Fe(H_2O)_6]^{2+}$ into $[Fe_4S_3(NO)_7]^-$ in this reaction requires reduction of iron from iron(II) to a mean oxidation number of $-\frac{1}{2}$ (see Section V,C, for discussion of the bonding in $[Fe_4S_3(NO)_7]^-$), spontaneous self-assembly to form the tetranuclear anion, and spin coupling to yield a diamagnetic ground state. Neither the mechanism nor the stoichiometry of this reaction is clear, although Brauer (*20*) gives an equation in which 170 mol of reactants give 102 mol of products (excluding water of crystallization).

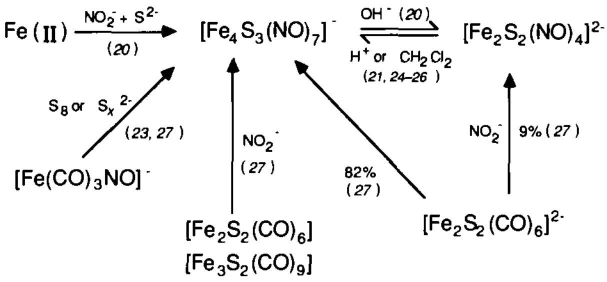
Salts of $[Fe_2S_2(NO)_4]^{2-}$ are best prepared by Pavel's modification (*3*) of Roussin's original method (*1*), which is again described by Brauer (*20*). Reaction of $NH_4[Fe_4S_3(NO)_7]$ with aqueous sodium hydroxide yields $Na_2[Fe_2S_2(NO)_4]$, from which other salts may be prepared by metathesis: $(Et_4N)_2[Fe_2S_2(NO)_4]$ is conveniently prepared from $NH_4[Fe_4S_3(NO)_7]$ by reaction with Et_4NOH (*21*). While $Na_2[Fe_2S_2(NO)_4]$ is insoluble in ether and similar solvents, unlike $M^I[Fe_4S_3(NO)_7]$, salts such as $(R_4N)_2[Fe_2S_2(NO)_4]$ and $(Ph_3PNPPh_3)_2[Fe_2S_2(NO)_4]$ are readily soluble in solvents such as ether and ketones.

The mechanism of conversion of $[Fe_4S_3(NO)_7]^-$ into $[Fe_2S_2(NO)_4]^{2-}$ almost certainly involves fragmentation to mononuclear species, followed by reassembly. At neutral pH, $[Fe_4S_3(NO)_7]^-$ gives no ESR spectrum, but upon increasing the pH to 11, an ESR spectrum appears (*22*), which has subsequently been identified (*23*) as that of the mononuclear species $[Fe(NO)_2(SH)_2]^-$. As discussed in Section VI,B, such complexes play a central role in many of the reactions of both diiron and tetrairon–sulfur–nitrosyls, particularly those involving ligand substitution and change of nuclearity.

Just as reaction of $[Fe_4S_3(NO)_7]^-$ with strong alkali gives $[Fe_2S_2(NO)_4]^{2-}$, so also reaction of $[Fe_2S_2(NO)_4]^{2-}$ with strong acids, such as CF_3COOH or HBF_4, yields (*24*) not only $[Fe_2(SH)_2(NO)_4]$, the "acid" corresponding to Roussin's red salt, but also $[Fe_4S_3(NO)_7]^-$. A more surprising conversion of $[Fe_2S_2(NO)_4]^{2-}$ into $[Fe_4S_3(NO)_7]^-$ is achieved (*21, 25, 26*) simply by dissolving a salt of $[Fe_2S_2(NO)_4]^{2-}$ in methylene chloride. Using ^{15}N-labeled material, the sole species detectable by ^{15}N NMR spectroscopy is $[Fe_4S_3(^{15}NO)_7]^-$ (*21, 25*), while, on a preparative scale (*26*), salts of $[Fe_4S_3(NO)_7]^-$ can be isolated in yields of around 60%.

Both $[Fe_4S_3(NO)_7]^-$ and $[Fe_2S_2(NO)_4]^{2-}$ can also be synthesized by carbonyl displacements from appropriate iron–carbonyl precursors. The complex $[Fe_4S_3(NO)_7]^-$ can in fact be formed from mono-, di-, or trinuclear iron–carbonylate species. Salts of $[Fe(CO)_3NO]^-$ react with elemental sulfur or with polysulfide to yield $[Fe_4S_3(NO)_7]^-$ (*23, 27*), while nitrosylations using sodium nitrite in aqueous ethanol of $[Fe_2S_2(CO)_6]$, $[Fe_2S_2(CO)_6]^{2-}$, and $[Fe_3S_2(CO)_9]$ all give $[Fe_4S_3(NO)_7]^-$ in yields of ~80% (*27*); in addition, the reaction with $[Fe_2S_2(CO)_6]^{2-}$ yields $[Fe_2S_2(NO)_4]^{2-}$ (9%).

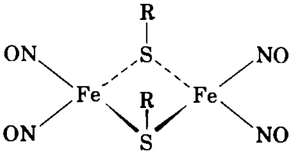
These transformations are summarized in Scheme 1.



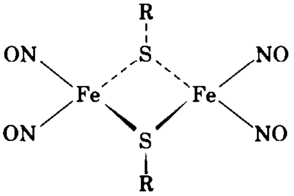
SCHEME 1. Synthetic routes to $[Fe_4S_3(NO)_7]^-$ and $[Fe_2S_2(NO)_4]^{2-}$. Numbers in parentheses are references.

B. $[Fe_2(SR)_2(NO)_4]$

Neutral $[Fe_2(SR)_2(NO)_4]$ complexes, **3a** and **3b**, having a wide range of substituents R, are now known. When R is alkyl or aryl, the complexes can be synthesized from mono-, di-, or tetrairon precursors, and this forms a convenient basis for the classification of synthetic routes to $[Fe_2(SR)_2(NO)_4]$.



3a



3b

1. *Synthesis from Mononuclear Precursors*

a. Iron(II) Salts. Reaction of nitric oxide with a mixture of an iron(II) salt, conveniently iron(II) sulfate, and a thiol RSH in strongly alkaline aqueous solution gives the corresponding complex $[Fe_2(SR)_2(NO)_4]$ in yields around 80% (*4, 5, 12, 20*) [Eq. (1)].

$$4FeSO_4 + 8KOH + 2RSH + 4NO \longrightarrow [Fe_2(SR)_2(NO)_4] + Fe_2O_3 + 4K_2SO_4 + 5H_2O \tag{1}$$

b. $[Fe(CO)_2(NO)_2]$. The mixed dicarbonyl–dinitrosyl reacts with PhSH to yield $[Fe_2(SPh)_2(NO)_4]$ (*28*), and with Me_2S_2 to give $[Fe_2(SMe)_2(NO)_4]$ [Eq. (2)] (*27*).

$$2[Fe(CO)_2(NO)_2] + Me_2S_2 \longrightarrow [Fe_2(SMe)_2(NO)_4] + 4CO \tag{2}$$

In each case, it is the carbonyl ligands which are displaced rather than the nitrosyl ligands. In a similar manner, the reaction of polysulfide (*23, 27*) with $[Fe(CO)_3NO]^-$ causes displacement of carbonyl, rather than nitrosyl, to yield $[Fe_4S_3(NO)_7]^-$ (see Section II,A).

c. $[Fe(NO)(S_2CNMe_2)_2]$. The reaction of the mononitrosyl complex with an excess of MeS^- provides the dinitrosyliron product $[Fe_2(SMe)_2(NO)_4]$ in 24% yield (*23*); this reaction proceeds via the mononuclear dinitrosyl $[Fe(NO)_2(SR)_2]^-$ and illustrates the ready interchange between $Fe(NO)^{2+}$ fragments and $Fe(NO)_2{}^+$ fragments, which will be discussed further in Section VI,B.

d. $[Fe(CO)_3NO]^-$. In another reaction illustrating the conversion of a mononitrosyliron source into a dinitrosyliron product by the action of RS^-, $(Ph_3PNPPh_3)[Fe(CO)_3NO]$ gave with MeSNa a 78% isolated yield of $[Fe_2(SMe)_2(NO)_4]$ (*23*). As with the corresponding reaction of $[Fe(NO)(S_2CNMe_2)_2]$ (see above), the reaction proceeds via $[Fe(NO)_2(SMe)_2]^-$. Similarly, reactions of $[Fe(CO)_3NO]^-$ with *i*-PrS^- or *t*-BuS^- gave $[Fe(NO)_2(SPr^i)_2]^-$ and $[Fe(NO)_2(SBu^t)_2]^-$, respectively, as precursors (see below) of the corresponding dinuclear $[Fe_2(SR)_2(NO)_4]$ (*23*).

e. $[Fe(NO)_2(SR)_2]^-$. Any process which gives rise to mononuclear complexes of the type $[Fe(NO)_2(SR)_2]^-$ ($R \neq H$) can also yield dinuclear $[Fe_2(SR)_2(NO)_4]$ (*23*). The mononuclear species are favored by highly polar environments such as DMF solution, but addition of toluene or a similar noncoordinating solvent of low polarity causes loss of RS^- and dimerization [Eq. (3)]; the reaction is reversible (*23*).

$$2[Fe(NO)_2(SR)_2]^- \underset{\text{DMF, } +2RS^-}{\overset{\text{toluene, } -2RS^-}{\rightleftharpoons}} [Fe_2(SR)_2(NO)_4] \tag{3}$$

2. *Synthesis from Dinuclear Precursors*

a. $[Fe_2S_2(NO)_4]^{2-}$. Probably the most versatile route to neutral $[Fe_2(SR)_2(NO)_4]$ complexes is provided by the reaction between $[Fe_2S_2(NO)_4]^{2-}$, acting as nucleophile, and molecular halides, RX, acting as electrophiles [Eq. (4)]. When R is an organic group this method is restricted to groups R containing a saturated α-carbon atom, but subject to this constraint has been widely employed for $R = CH_3$ (*24, 29*), Et (*3, 29*), C_3H_5(allyl) (*29*), $PhCH_2$ (*29, 30*), $HC{\equiv}CCH_2$, Me_3SiCH_2, and $CH_3C(O)CH_2$ (*29*).

$$[Fe_2S_2(NO)_4]^{2-} + 2RX \longrightarrow 2X^- + [Fe_2(SR)_2(NO)_4] \tag{4}$$

Organometallic halides may also be employed as the electrophile in Eq. (4); thus by use of Ph_3SnCl, Me_3SnBr, Ph_3PbBr, PhHgCl (*29*), or CH_3HgCl (*31*), the corresponding $[Fe_2(SMR_x)_2(NO)_4]$ complexes were obtained in yields ranging from 33% for $[Fe_2(SHgPh)_2(NO)_4]$ to 99% for $[Fe_2(SPbPh_3)_2(NO)_4]$ (*29*). These derivatives are all reddish crystalline solids, usually somewhat air sensitive as solids, and very air sensitive in solution.

The use of organic gem dihalides as electrophiles does not appear to have been reported, although no success was reported in attempts to react $[Fe_2S_2(NO)_4]^{2-}$ with Me_2SnCl_2 or Ph_2PbCl_2 (*29*), presumably because the S····S bite is too large for effective chelation to tin(IV) or lead(IV).

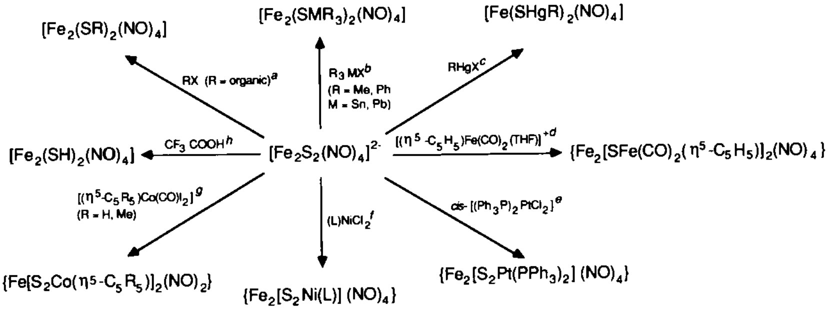
For successful reaction of $[Fe_2S_2(NO)_4]^{2-}$ at transition metal centers a strongly electrophilic metal is required; thus while no reaction was observed (*29*) with $[(\eta^5\text{-}C_5H_5)Fe(CO)_2Br]$, the more electrophilic cationic complex $[(\eta^5\text{-}C_5H_5)Fe(CO)_2(THF)]BF_4$ reacted to provide a 90% yield of the air-stable $[Fe_2\{SFe(CO)_2(\eta^5\text{-}C_5H_5)\}_2(NO)_4]$.

Just as group-14 gem dihalides appear to be size limited in their reactions with $[Fe_2S_2(NO)_4]^{2-}$, so too do cis dihalide complexes of the group-10 metals. Although *cis*-$[(Ph_3P)_2PtCl_2]$ reacts with $[Fe_2S_2(NO)_4]^{2-}$ to provide a 95% yield of $[Fe_2\{S_2Pt(PPh_3)_2\}(NO)_4]$ (*32*), attempts to prepare analogous complexes containing the smaller homologs nickel and palladium failed (*29*). However, reaction with $[NiCl_2(Ph_2PCH_2CH_2PPh_2)]$ gave (*30*) $[Fe_2\{S_2Ni(Ph_2PCH_2CH_2PPh_2)\}(NO)_4]$. In contrast to the formation of this platinum complex, which proceeds simply by nucleophilic displacement of chloride by the sulfur in $[Fe_2S_2(NO)_4]^{2-}$, reaction of $[Fe_2S_2(NO)_4]^{2-}$ with the cobalt gem dihalides $[(\eta^5\text{-}C_5R_5)Co(CO)I_2](R = H$ or Me) yielded the novel trinuclear cluster $[Fe(\mu_3\text{-}S)_2\{Co(\eta^5\text{-}C_5R_5)\}_2(NO)_2]$ (*29*), in which the iron is bound not only to two terminal NO ligands but to two μ_3-sulfur ligands and to two cobalt centers.

With the proton as electrophile, the primary product from $[Fe_2S_2(NO)_4]^{2-}$ is $[Fe_2(SH)_2(NO)_4]$ as noted earlier (Section II,A), but this is susceptible to decomposition, yielding $[Fe_4S_3(NO)_7]^-$ (*24*).

The reactions of $[Fe_2S_2(NO)_4]^{2-}$ with electrophiles are summarized in Scheme 2.

b. $[Fe_2(SR)_2(CO)_6]$. When R is an organic group, the reaction of $[Fe_2S_2(NO)_4]^{2-}$ with RX cannot always be applied; for example, if R = aryl then RX will not react. However, the carbonyl complexes



SCHEME 2. Reactions of $[Fe_2S_2(NO)_4]^{2-}$ with electrophiles. [a]Refs. *3*, *24*, *29*, and *30*. [b]Ref. *29*. [c]Refs. *29* and *31*. [d]Ref. *29*. [e]Ref. *32*. [f]Ref. *30*: $L = Ph_2PCH_2CH_2PPh_2$. [g]Ref. *29*. [h]Ref. *24*.

$[Fe_2(SR)_2(CO)_6]$, which are readily available from the reactions of R_2S_2 with $[Fe_3(CO)_{12}]$ (*33*) and of RSH with $[Fe_2(CO)_9]$ (*34*), can be nitrosylated in reactions which replace three carbonyl ligands by two nitrosyl ligands. Nitrosylation can be effected either by use of nitric oxide gas (*27, 29*) or by use of sodium nitrite in aqueous ethanol (*27*) or, better, in dimethylformamide (DMF) (*25*). It is usually more convenient to employ nitric oxide if complexes of normal isotopic composition are required, but for ^{15}N labeling the use of sodium nitrite in DMF is the more convenient and economical route.

The mechanism of the reaction of $[Fe_2(SR)_2(CO)_6]$ with nitric oxide does not seem to have been investigated. The corresponding reaction with nitrite in DMF proceeds (*25*) via the mononuclear complex $[Fe(NO)_2(SR)_2]^-$ (see Section II,B,1), but it is not yet known how this complex is formed from $[Fe_2(SR)_2(CO)_6]$.

c. $[Fe_2I_2(NO)_4]$. This iodo-bridged complex reacts in tetrahydrofuran (THF) solution with thiols (RSH) in the presence of a base B (*30*), conveniently triethylamine, to yield the corresponding $[Fe_2(SR)_2(NO)_4]$ [Eq. (5)].

$$[Fe_2I_2(NO)_4] + 2RSH + 2B \longrightarrow [Fe_2(SR)_2(NO)_4] + 2BH^+I^- \qquad (5)$$

Study of this reaction by EPR spectroscopy (*35*) has shown that it proceeds via the mononuclear complexes $[Fe(NO)_2I]$ and $[Fe(NO)_2(SR)_2]^-$.

As well as introducing this fairly straightforward use of $[Fe_2I_2(NO)_4]$ and its extension, by reaction with PhELi (E = S, Se, or Te) [Eq. (6)], Rauchfuss and Weatherill have developed (*30*) an ingenious synthesis of $[Fe_2E_2(NO)_4]^{2-}$ [Eq. (7)].

$$[Fe_2I_2(NO)_4] + 2PhELi \longrightarrow 2LiI + [Fe_2(EPh)_2(NO)_4] \qquad (6)$$

$$[Fe_2I_2(NO)_4] + 2Li_2E \longrightarrow 2LiI + Li_2[Fe_2E_2(NO)_4] \qquad (7)$$

The products $[Fe_2E_2(NO)_4]^{2-}$ can be alkylated in the usual way (see Section II,B,2). The advantage of using $[Fe_2I_2(NO)_4]$ as starting material lies in the fact that stepwise displacement of the μ-iodo ligands is possible, by either E^{2-} or by RE^-; thus a mixed chalcogen derivative such as $[Fe_2(SCH_2Ph)(SePh)(NO)_4]$ or $[Fe_2(SCH_2Ph)(SeCH_2Ph)(NO)_4]$ can be synthesized [Eqs. (8) and (9)].

$$[Fe_2I_2(NO)_4] \xrightarrow{PhSeLi} [Fe_2I(SePh)(NO)_4] \xrightarrow{PhCH_2SH/Et_3N} [Fe_2(SCH_2Ph)(SePh)(NO)_4] \qquad (8)$$

$$[Fe_2I_2(NO)_4] \xrightarrow{Se^{2}} [Fe_2I(Se)(NO)_4]^- \xrightarrow{PhCH_2SH/Et_3N}$$
$$[Fe_2(SCH_2Ph)(Se)(NO)_4]^- \xrightarrow{PhCH_2Cl} [Fe_2(SCH_2Ph)(SeCH_2Ph)(NO)_4] \quad (9)$$

3. *Synthesis from Tetranuclear Precursors*

As noted in Section II,B,1, any process which leads to the mononuclear anionic intermediates $[Fe(NO)_2(SR)_2]^-$ can also provide, by loss of RS^-, the neutral dinuclear $Fe_2(SR)_2(NO)_4$. Both $[Fe_4S_3(NO)_7]^-$ and $[Fe_4S_4(NO)_4]$ have been shown (*23*) by EPR spectroscopy to react with MeS^-, yielding $[Fe(NO)_2(SMe)_2]^-$; the corresponding dinuclear $[Fe_2(SMe)_2(NO)_4]$ has been isolated (*23*) from these reactions in yields of 46 and 13%, respectively.

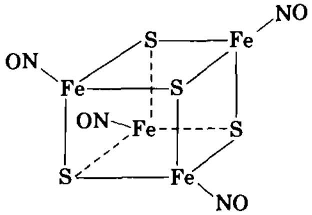
C. $[Fe_4S_4(NO)_4]$ AND RELATED CUBANE-TYPE CLUSTERS

1. *$[Fe_4S_4(NO)_4]$ and $[Fe_4S_4(NO)_4]^-$*

The reaction between $Hg[Fe(CO)_3NO]_2$ and elemental sulfur in refluxing toluene provides (*36, 37*) practical yields of the cubane-type tetranuclear $[Fe_4S_4(NO)_4]$ [Eq. (10)].

$$2Hg[Fe(CO)_3NO]_2 + \tfrac{1}{2}S_8 \longrightarrow [Fe_4S_4(NO)_4] + 2HgS + 12CO \quad (10)$$

This synthesis provides another example, comparable to that of $[Fe_4S_3(NO)_7]^-$, of the spontaneous self-assembly of a tetranuclear species 4 from a mononuclear precursor in a one-stage procedure.



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It is instructive, in this context, to compare the case of assembly of both nitrosylated iron–sulfur tetranuclear clusters and the related clusters with pendant thiolate groups (*13*), with the laborious and stepwise initial synthesis (*38*) of cubane C_8H_8; this comparison is, of course, simply one between thermodynamically controlled processes, in the case of the iron–sulfur systems, and kinetically controlled reactions for C_8H_8 synthesis.

The identical $[Fe_4S_4(NO)_4]$ can also be synthesized more conveniently by reflux of $Na[Fe_4S_3(NO)_7]$ with elemental sulfur in toluene (*27*); it is not yet clear whether this process involves simply the completion of the Fe_4S_4 framework by addition of one atom of sulfur to the existing Fe_4S_3 framework, or whether it proceeds by means of fragmentation, perhaps to mononuclear intermediates, followed by subsequent reformation of the iron–sulfur skeleton. Whatever the mechanism, it is clear that the formation of $[Fe_4S_4(NO)_4]$ from $[Fe_4S_3(NO)_7]^-$ is subject to subtle factors involving both the counterion and the solubility of the products and reactants, since even on prolonged (>7 days) reflux in toluene the salt (Ph_3PNPPh_3)-$[Fe_4S_3(NO)_7]$ did not react with sulfur to yield any $[Fe_4S_4(NO)_4]$. A similar contrast in fact obtains in the reactions with sulfur and polysulfide with the mercurial $Hg[Fe(CO)_3NO]_2$: with elemental sulfur in toluene the product is $[Fe_4S_4(NO)_4]$ (*36, 37*), but with polysulfide in methanol $[Fe_4S_3(NO)_7]^-$ is formed (*27*).

Electrochemical reduction—or chemical reduction by $[(\eta^5\text{-}C_5H_5)_2Co]$, sodium amalgam, or potassium benzophenone ketyl—of $[Fe_4S_4(NO)_4]$ provides the monoanion $[Fe_4S_4(NO)_4]^-$ (*37*). Serious difficulty was experienced (*37*) in the isolation and characterization of salts of $[Fe_4S_4(NO)_4]^-$, and earlier attempts resulted instead in the isolation of salts of $[Fe_4S_3(NO)_7]^-$ (*37, 39*). The sequence summarized in Eq. (11) must again involve a major structural reorganization:

$$[Fe_4S_4(NO)_4] \xrightarrow{e} [Fe_4S_4(NO)_4]^- \longrightarrow [Fe_4S_3(NO)_7]^- + \text{unidentified by-products} \tag{11}$$

It is probable, although not proved, that the transformation of $[Fe_4S_4(NO)_4]^-$ to $[Fe_4S_3(NO)_7]^-$ proceeds by means of fragmentation to mononuclear intermediates, followed by reassembly.

The cubane-type cluster $[Fe_4S_4(NO)_4]$ gives $[Fe_4S_3(NO)_7]^-$ not only upon reduction but also upon aerial oxidation in THF solution (*37*). This immediately suggests, because of the instability of $[Fe_4S_4(NO)_4]$ with respect to fragmentation upon both electron addition and electron removal, that the frontier orbitals of $[Fe_4S_4(NO)_4]$ are localized in an electron-precise Fe_4 framework; the bonding in $[Fe_4S_4(NO)_4]$ and like clusters is discussed in Section V,C.

2. *$[Fe_4S_2(NO)_4(NCMe_3)_2]$ and $[Fe_4S_2(NO)_4(NCMe_3)_2]^-$*

Formally isoelectronic with $[Fe_4S_4(NO)_4]$ is the as yet unknown $[Fe_4(NO)_4(NCMe_3)_4]$. Attempts to prepare this latter cluster, in order to effect comparison with the known (*40*) stoichiometric analog

$[Co_4(NO)_4(NCMe_3)_4]$, by reaction of $Hg[Fe(CO)_3NO]_2$ with the sulfur diimide $(Me_3CN)_2S$ under a wide range of conditions yielded (*36, 41*) instead $[Fe_4S_2(NO)_4(NCMe_3)_2]$, in which only two of the triply bridging sulfur ligands present in $[Fe_4S_4(NO)_4]$ have formally been replaced by μ_3-NCMe ligands. For this complex also, sodium amalgam reduction yields (*41*) the monoanion $[Fe_4S_2(NO)_4(NCMe_3)_2]^-$, which appears to be less prone to rearrangement than $[Fe_4S_4(NO)_4]^-$.

D. Other Fe–S–NO Complexes

1. "$[Fe_3S_2(NO)_5]^-$"

Iron–sulfur systems containing three iron atoms are uncommon, and so the reported synthesis (*42*) of such a trinuclear anion $[Fe_3S_2(NO)_5]^-$ was of great interest, particularly as it was also reported that this anion, although an even-electron species, gave ESR spectra under a wide range of conditions.

It is therefore unfortunate that attempts to repeat the synthesis of salts containing $[Fe_3S_2(NO)_5]^-$ according to the published (*42*) procedure have all, without exception, yielded the corresponding salts of $[Fe_4S_3(NO)_7]^-$ (*43*). Neither could $[Fe_3S_2(NO)_5]^-$ be identified as a nitrosylation product of the carbonyl cluster $[Fe_3S_2(CO)_9]$ in which the Fe_3S_2 framework is preformed (*27*).

Other aspects of the report (*42*) on $[Fe_3S_2(NO)_5]^-$ are surprising. Elemental analysis of the ammonium salt was reported to distinguish between iron(II) and iron(III) in $[Fe_3S_2(NO)_5]^-$, but to find these two types of iron present in equal numbers is most unusual for a triiron complex. Second, the molecular weight of the potassium salt was measured as 420 by mass spectrometry. This value is close to the M/Z of 421 calculated for the most abundant isotopic form of the ion-pair cation $[KFe_3S_2(NO)_5]^+$. Finally, the ESR spectrum reported is that of a dinitrosyliron species, which bears a remarkable resemblance to that reported (*22*) for a complex formed from Fe(II) and nitric oxide in aqueous alkaline solution.

Until further evidence is forthcoming it is necessary, therefore, to treat the report (*42*) of the preparation and properties of $[Fe_3S_2(NO)_5]^-$ with some caution.

2. $[Fe_2(S_2O_3)_2(NO)_4]^{2-}$

The synthesis of salts containing this anion was first reported in 1895 by Hofmann and Wiede (*4*), and subsequently confirmed by

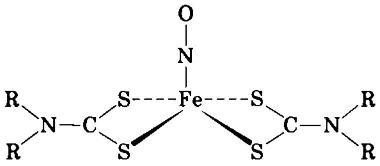
Manchot (*44*) and by Brauer (*45*). Reaction of an iron(II) salt with potassium thiosulfate and nitric oxide yields the required anion [Eq. (12)].

$$2FeSO_4 + 4K_2S_2O_3 + 4NO \longrightarrow K_2[Fe_2(S_2O_3)_2(NO)_4] + K_2S_4O_6 + 2K_2SO_4 \quad (12)$$

This is similar to the synthesis of the neutral Roussin esters $[Fe_2(SR)_2(NO)_4]$ from iron(II), RSH, and nitric oxide [Eq. (1), Section II,B,1], except that in Eq. (1) the iron(II) initially present undergoes disproportionation to Fe(I), which is present in the product $[Fe_2(SR)_2(NO)_4]$, and Fe(III), which is removed as oxide. In Eq. (12), by contrast, the iron(II) is reduced to Fe(I) by excess of thiosulfate, which is itself oxidized to tetrathionate. Apart from its diamagnetism (*4*), practically nothing is known about this anion.

3. *[Fe(NO)(S$_2$CNR$_2$)$_2$] and Related Complexes*

Reaction of an iron(II) salt, conveniently the sulfate, with sodium dialkyldithiocarbamate $[R_2NCS_2]Na$ under nitric oxide provides excellent yields (>85%) of the iron(I) complexes $[Fe(NO)(S_2CNR_2)_2]$ (structure **5**) (*46*). Oxidation of the diethyldithiocarbamate derivative with molecular bromine or iodine or with nitrogen(IV) oxide yielded *cis*-$[Fe(NO)X(S_2CNEt_2)_2]$, for X = Br, I, or NO_2 (*46*), although NO did not react. Subsequent study of the oxidation of the dimethyl analog $[Fe(NO)(S_2CNMe_2)_2]$ by nitrogen(IV) oxide showed (*47*) that at low temperature (−60°C, $CHCl_3$ solution) the initial product is *trans*-$[Fe(NO)(NO_2)(S_2CNMe_2)_2]$, but that this isomer is rapidly converted to *cis*-$[Fe(NO)(NO_2)(S_2CNMe_2)_2]$ at 5°C or above.



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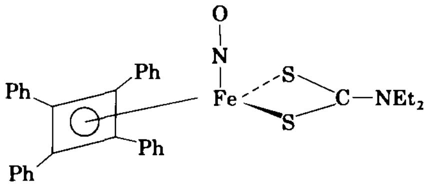
The iron cyclobutadiene complex $[(\eta^4\text{-}C_4Ph_4)Fe(CO)_2NO]^+$ undergoes replacement of both carbonyl ligands with $Et_2NCS_2^-$, although with retention of the nitrosyl ligand (*48*) to yield $[(\eta^4\text{-}C_4Ph_4)Fe(NO)(S_2CNEt_2)]$. structure **6**.



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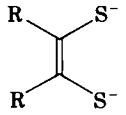
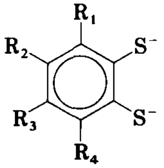
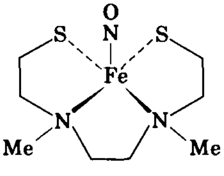


7 *a* R = CN
b R = Ph
c R = CF_3

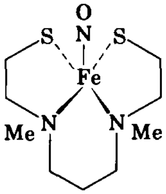


8 *a* $R_1, R_3, R_4 = H; R_2 = CH_3$
b $R_1–R_4 = Cl$

In $[Fe(NO)(S_2CNR_2)_2]$ the iron is ligated by four sulfur atoms as well as by the nitrosyl ligand; similar $Fe(NO)S_4$ chromophores are found (*49*) in complexes of dithiolenes (**7**) and dithiols (**8**). For both dithiolene and dithiol derivatives, reaction of $[FeL_2]^{2-}$ (L = **7** or **8**) with NO gas yields the nitrosyl derivatives $[Fe(NO)L_2]^-$ (*50*), in which the nitrosyl ligand has effected a net oxidation. Certain of the mononegative complexes can be oxidized by iodine to neutral $Fe(NO)L_2$ or reduced with borohydride to dinegative $[Fe(NO)L_2]^{2-}$ (*50*).

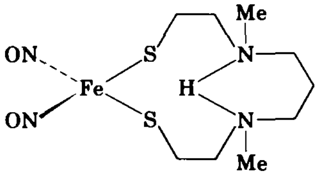


9 [FeL(NO)]



10 [FeL′(NO)]

The $Fe(NO)S_2N_2$ chromophore found in complexes **9**, [FeL(NO)], and **10**, [FeL′(NO)], is almost identical to that in $[Fe(NO)(S_2CNR_2)_2]$ (*49*). These complexes can be prepared by reaction of NO, NO^+, or NO_2^+ with the dimeric complexes $[Fe_2\{(CH_2)_2(NMe\ CH_2CH_2S)_2\}_2]$, i.e., $(FeL)_2$, and $[Fe_2\{(CH_2)_3(NMe\ CH_2CH_2S)_2\}_2]$, i.e., $(FeL')_2$, respectively. An alternative synthesis of FeL′(NO) has been described (*51*): reaction of



11 $[Fe(NO)_2(L'H)]$

$[Fe(NO)_2Br_2]^-$ with $L'H_2$ provides two products, $[FeL'(NO)]$ and $[Fe(NO)_2(L'H)]$ (11), which is a neutral analog of the anions $[Fe(NO)_2(SR)_2]^-$ readily available from $[Fe_2(SR)_2(NO)_4]$ (*23*).

E. SELENIUM ANALOGS

The number of iron–selenium–nitrosyl complexes is substantially smaller than the iron–sulfur–nitrosyl species, as considerably less work in this area has been reported. However there are a number of differences between the sulfur systems and their analogs containing selenium or tellurium. For selenium it is convenient to divide the complexes into three classes, dependent upon the stoichiometry of the metal–chalcogen framework.

1. Fe_2Se_2 *Complexes*

The conversion of $[Fe_2I_2(NO)_4]$ to $[Fe_2Se_2(NO)_4]^{2-}$ (*26, 30*) was described earlier [Eq. (7), Section II,B,2] along with the subsequent alkylation of $[Fe_2Se_2(NO)_4]^{2-}$; the neutral species $[Fe_2(SeR)_2(NO)_4]$ can also be obtained (*26, 30*) by reaction of RSe^- with $[Fe_2I_2(NO)_4]$, [Eq. (6), Section II,B,2].

2. Fe_4Se_4 *Complexes*

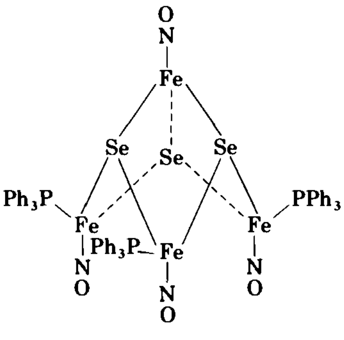
Reaction of $Hg[Fe(CO)_3NO]$ with elemental selenium in refluxing toluene (*52*) proceeds just like the reaction of this mercurial with elemental sulfur (*36, 37*) and gives the cubane-type tetranuclear cluster $[Fe_4Se_4(NO)_4]$. This cluster can also be readily synthesized by reaction of $Na[Fe_4Se_3(NO)_7]$ with elemental selenium, also in refluxing toluene (*53*).

Reduction of $[Fe_4Se_4(NO)_4]$ by a stoichiometric quantity of potassium metal in the presence of 2,2,2-cryptand yielded the salt $[K(2,2,2\text{-crypt})]^+[Fe_4Se_4(NO)_4]^-$ (*52*), use of excess barium metal under similar conditions gave the rather unstable dinegative anion $[Fe_4Se_4(NO)_4]^{2-}$, which can also be made by further reduction of mononegative anion by excess potassium metal.

3. Fe_4Se_3 *Complexes*

Three routes have been described to the anion $[Fe_4Se_3(NO)_7]^-$, the selenium analog of the Roussin black anion. Reaction of iron(II) sulfate with sodium nitrite and sodium hydrogen selenide provides $Na[Fe_4Se_3(NO)_7]$ (*27*) in a reaction entirely analogous to Roussin's original synthesis of the anion $[Fe_4S_3(NO)_7]^-$ (*1*). Likewise, just as $[Fe_2S_2(NO)_4]^{2-}$ is converted, in CH_2Cl_2 solution, to $[Fe_4S_3(NO)_7]^-$ (Section II,A), so too the Ph_4As^+ salt of $[Fe_2Se_2(NO)_4]^{2-}$ is converted into $(Ph_4As)[Fe_4Se_3(NO)_7]$ (*26*) in practical yield simply by stirring it in CH_2Cl_2 for half an hour. Similarly, synthesis of $[Fe_2Se_2(NO)_4]^{2-}$ from $[Fe_2I_2(NO)_4]$ followed by acidification with glacial acetic acid, without isolation of the intermediate $Li_2[Fe_2Se_2(NO)_4]$, yields, after addition of $(Ph_3PNPPh_3)Cl$, the Fe_4Se_3 salt $(Ph_3PNPPh_3)[Fe_4Se_3(NO)_7]$ in 77% yield in a one-pot process (*26*).

The reaction of the selenium cubane cluster $[Fe_4Se_4(NO)_4]$ with excess of Ph_3P, which often acts as a chalcogen abstractor as well as a ligand, yields (*52*) a product of composition $[Fe_4Se_3(NO)_4(PPh_3)_3]$ (**12**), whose X-ray structure (see Section III,E) shows that it resembles $[Fe_4Se_3(NO)_7]^-$ but with the equatorial nitrosyl ligands on the basal iron atoms replaced by triphenylphosphine.



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Reduction of $[Fe_4Se_3(NO)_4(Ph_3P)_3]$ by an excess of barium metal in THF solution in the presence of the 2,2,2-cryptand gave the $[Ba(2,2,2\text{-crypt})]^{2+}$ salt of the dinegative heptanitrosyl anion $[Fe_4Se_3(NO)_7]^{2-}$. Clearly the change from $[Fe_4Se_3(NO)_4(Ph_3P)_3]$ to $[Fe_4Se_3(NO)_7]^{2-}$

must involve major rearrangement involving not only loss of triphenylphosphine but reorganization from mononitrosyliron fragments to dinitrosyliron fragments.

F. TELLURIUM ANALOGS

In comparison with the sulfur and selenium systems, rather few iron–tellurium–nitrosyl complexes are known. One of the most productive techniques of study of this area has proved to be that employing $[Fe_2I_2(NO)_4]$ (*16, 30*). Thus reaction of $PhTe^-$ with $[Fe_2I_2(NO)_4]$ gave $[Fe_2(TePh)_2(NO)_4]$ [cf. Eq. (6), Section II,B,2], and Te^{2-} yielded $[Fe_2Te_2(NO)_4]^{2-}$ [cf. Eq. (7), Section II,B,2]. The anion $[Fe_2Te_2(NO)_4]^{2-}$ can be alkylated with electrophilic reagents such as BEt_3 or $PhCH_2Cl$ (*26*). Just as $[Fe_2S_2(NO)_4]^{2-}$ and $[Fe_2Se_2(NO)_4]^{2-}$ are spontaneously converted in CH_2Cl_2 solution into the tetrairon anions $[Fe_4X_3(NO)_7]^-$ ($X = S$ or Se), so also (*26*) $[Fe_2Te_2(NO)_4]^{2-}$ upon similar treatment gives $[Fe_4Te_3(NO)_7]^-$, although salts of this anion have not yet been obtained analytically pure.

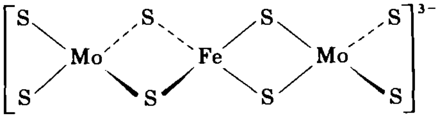
In contrast to the reactions of elemental sulfur and selenium with the mercurial $Hg[Fe(CO)_3NO]_2$ to give cubane-type clusters $[Fe_4X_4(NO)_4]$ ($X = S$ or Se) (*36, 37, 52*), the analogous reaction with elemental tellurium yielded (*52*) the nitrosyl-free cluster $[Fe_3Te_2(CO)_9]$. However, reaction of the mercurial either with a mixture of Ph_2Te_2 and elemental tellurium in refluxing toluene, or with $PhTeBr_3$ in cold methanol, yielded a diiron–nitrosyl $[Fe_2(TePh)_2(NO)_4]$ identical with that formed (*26, 30*) by reaction of $PhTe^-$ with $[Fe_2I_2(NO)_4]$. Reduction of $[Fe_2(TePh)_2(NO)_4]$ with an excess of barium metal yielded the corresponding dianion $[Fe_2(TePh)_2(NO)_4]^{2-}$ (*52*).

G. HETEROMETALLIC IRON–SULFUR–NITROSYL CLUSTERS

A variety of routes have been employed for the synthesis of heterometallic clusters containing Fe(NO)S fragments, and examples of such systems have been described in which the second metal is V, Mo, Co, Ni, and Pt; it seems probable, given the variety of potential synthetic approaches to such mixed metal systems, that many more examples await discovery.

1. Synthesis by Nitrosylation of Preformed Heterometallic Aggregates

When the heterotrimetallic anion $Fe(S_2MoS_2)_2^{3-}$ (**13**), was treated with NO gas in DMF solution, the reaction product isolated (*54*) in 50% yield was a salt of the heterometallic iron–dinitrosyl



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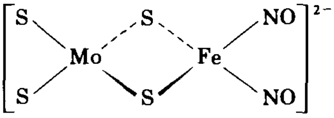

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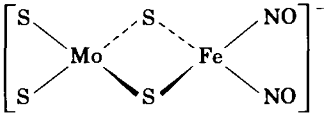
$[S_2MoS_2Fe(NO)_2]^{2-}$ (**14**). The tungsten analog of **14** was synthesized in a similar manner (*54*).

2. *Synthesis by Use of Sulfur-Containing Anions as Nucleophiles*

The reactions of $[Fe_2S_2(NO)_4]^{2-}$ with complexes of nickel (*30*) and platinum (*32*) to yield heterometallic Fe_2MS_2 clusters have already been described (Section II,B,2).

The tetrathiomolybdate anion $[MoS_4]^{2-}$ acts as a chelating ligand toward iron in both diiron complexes $[Fe_2(SR)_2(NO)_4]$ and tetrairon complexes $[Fe_4S_3(NO)_7]^-$ and $[Fe_4S_4(NO)_4]$ to yield two paramagnetic iron–nitrosyls which have been assigned (*55*) the constitutions **15** and **16**:



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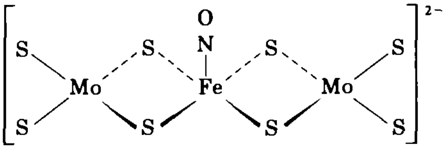

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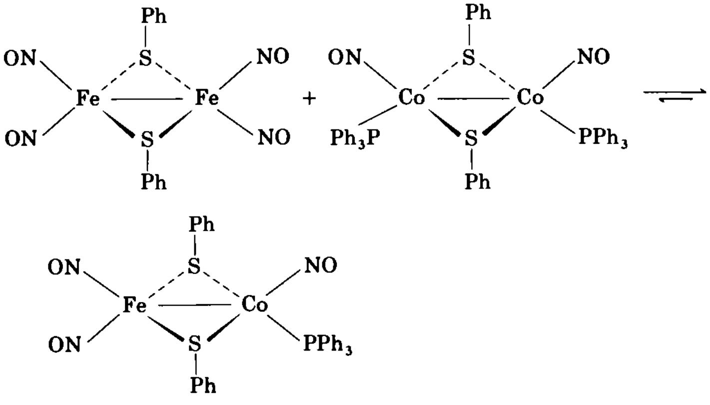
Complex **15** differs from **14** only in the overall oxidation level, while complex **16** is clearly related to the dithiocarbamate complex **5** (Section II,D,3).

3. Synthesis via Exchange Reactions

From the reaction of $[Fe_2(SPh)_2(NO)_4]$ with the dinuclear cobalt complex $[Co_2(SPh)_2(NO)_2(PPh_3)_2]$, the mixed-metal nitrosyl **17** was isolated by chromatography in 70% yield (*26*) [Eq. (13)]:



17

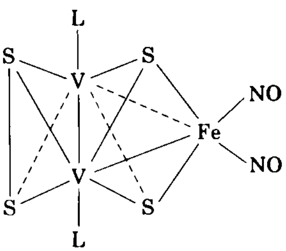
(13)

Complex **17** can also be formed in low yield (*26*) along with $[Fe_2(SPh)_2(NO)_4]$ by the reaction of $[Co_2(SPh)_2(NO)_2(PPh_3)_2]$ with $[Fe_2(SPh)_2(CO)_6]$.

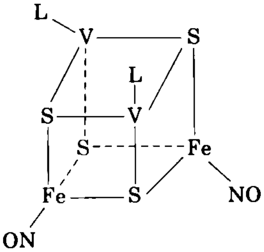
4. Synthesis from Sulfur-Rich Metal Complexes

The mercurial $Hg[Fe(CO)_3NO]_2$ reacts with elemental sulfur S_8 to yield the cubane-type cluster $[Fe_4S_4(NO)_4]$ (*36, 37*); it is not therefore entirely unexpected that metal complexes rich in sulfur can likewise react with this mercurial to produce novel heterometallic nitrosyls.

Thus $[(\eta^5\text{-}C_5H_4Me)_2V_2S_4]$ reacts (*26, 56, 57*) with $Hg[Fe(CO)_3NO]_2$ to yield successively the complexes $[(\eta^5\text{-}C_5H_4Me)_2V_2S_4Fe(NO)_2]$ (**18**)

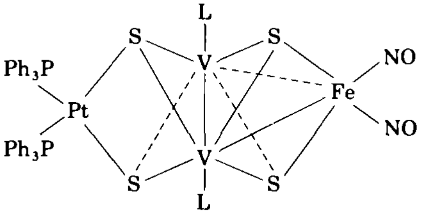


18 L = C_5H_4Me



19

and the cubane-type cluster $[(\eta^5\text{-}C_5H_4Me)_2V_2S_4Fe_2(NO)_2]$ (**19**). In like manner $[(\eta^5\text{-}C_5H_4Me)_2Mo_2S_4]$ reacts (*58*) with $Hg[Fe(CO)_3NO]_2$ to give $[(\eta^5\text{-}C_5H_4Me)_2Mo_2S_4Fe(NO)_2]$.



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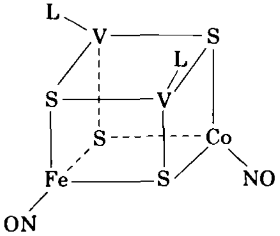

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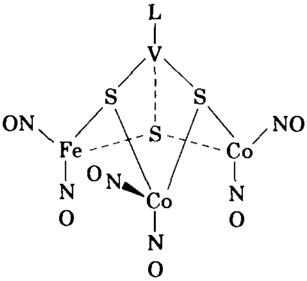
Both **18** and **19** are, furthermore, effective precursors for heterometallic nitrosyls containing three different metals. Thus (*26*) **18** reacts with $[(Ph_3P)_2Pt(C_2H_4)]$ to give $[(\eta^5\text{-}C_5H_4Me)_2V_2S_4\{Fe(NO)_2\}\{Pt(PPh_3)_2\}]$ (**20**), while **19** reacts (*26, 56*) with $[Co(NO)(CO)_3]$ in the presence of Me_3NO to give the cubane-type complex **21** containing a V_2FeCoS_4 core.

The trinuclear complex **18** reacts with $[Co(NO)_2I]_x$ under reducing conditions (Zn dust, MeLi, or $LiBEt_3H$) to provide a 44% yield of $[(\eta^5\text{-}C_5H_4Me)VS_3FeCo_2(NO)_6]$ (*26*), which has been assigned the constitution **22**; this complex has the same overall electron count as $[Fe_4S_3(NO)_7]^-$, and it was on this basis that the structure **22**, with its strong resemblance to $[Fe_4S_3(NO)_7]^-$, was proposed (*26*).



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Finally, a single example of desulfurization, using a tertiary phosphine, to effect cluster transformation, has been reported (*26*) for a heterometallic nitrosyl. Reaction of complex **18** $[(\eta^5\text{-}C_5H_4Me)_2V_2S_4Fe(NO)_2]$ with tributylphosphine provided $[(\eta^5\text{-}C_5H_4Me)_2V_2S_3Fe(NO)_2]$, of unknown constitution, in 80% yield.

III. Molecular Structure: X-Ray Crystallography

The principal objective of the earliest X-ray studies to be carried out on iron–sulfur–nitrosyl complexes, those on $[Fe_2(SEt)_2(NO)_4]$ (*10*) and $Cs[Fe_4S_3(NO)_7]$ (*11*), was the establishment of their gross chemical constitution. More recent X-ray studies have been concerned not only with gross structure, but additionally with detailed comparisons within series of similar species as a possible probe of electronic structure.

A. $[Fe_4S_3(NO)_7]^-$ AND $[Fe_2S_2(NO)_4]^{2-}$

The structure of $[Fe_4S_3(NO)_7]^-$ was initially determined for the cesium salt (*11*) and it was subsequently redetermined for the tetraphenylarsonium salt (*39*). In both salts the anion has the same overall structure, of essentially C_{3v} molecular symmetry, with remarkably similar dimensions. The anion contains a flattened Fe_4 tetrahedron, three faces of which are triply bridged by sulfur atoms. The unique apical iron carries a single nitrosyl ligand while the three basal irons each carry two nitrosyl ligands, which may be regarded as axial (approximately parallel to the threefold symmetry axis) and equatorial, respectively. Figure 1 shows the anion as in the Ph_4As^+ salt; in this salt the averaged Fe_a–Fe_b and Fe_b–Fe_b distances are 2.700 and 3.570 Å, respectively and the averaged Fe_a–S and Fe_b–S distances are 2.206 and 2.258 Å. All of the Fe–N–O groups fall into the category regarded as "linear," i.e., best described as based upon NO^+ rather than upon any other electronic form of the nitrosyl ligand (see Section V, for

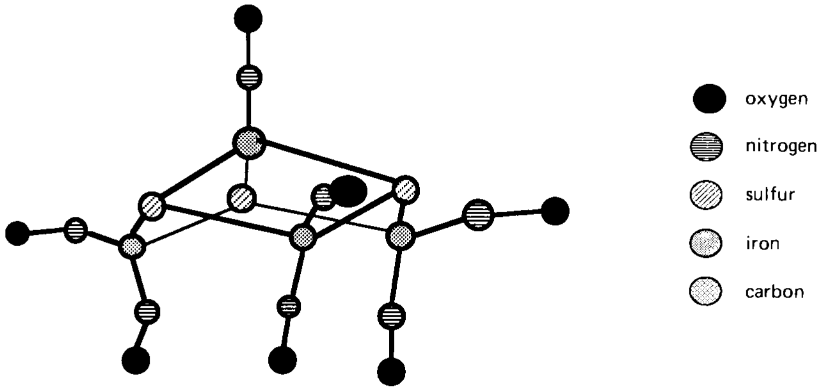


FIG. 1. The structure of the anion $[Fe_4S_3(NO)_7]^-$ as in the Ph_4As^+ salt. Redrawn from Ref. *39*.

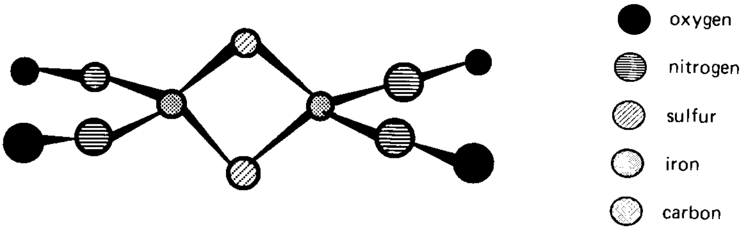


FIG. 2. The structure of the anion $[Fe_2S_2(NO)_4]^{2-}$ as in the Me_4N^+ salt. Redrawn from Ref. *59*.

discussion of electronic structures): the Fe_a–N–O angle is 176.3(9)°, the equatorial and axial Fe_b–N–O angles are 167.5 and 166.1°, respectively.

The structure of $[Fe_2S_2(NO)_4]^{2-}$ has been determined only recently (*59*): the tetramethylammonium salt contains two crystallographically distinct anions in the asymmetric unit, each of which has approximate D_{2h} molecular symmetry, although only C_i crystallographic symmetry. Thus the Fe_2S_2 fragment is planar, with an average Fe–S distance of 2.244 Å, very similar to the S–$Fe(NO)_2$ distance, 2.258 Å in $[Fe_4S_3(NO)_7]^-$ (*39*). Likewise, the Fe–Fe distance of 2.714 Å in $[Fe_2S_2(NO)_4]^{2-}$ is similar to the Fe_a–Fe_b distance, 2.700 Å, in $[Fe_4S_3(NO)_7]^-$. The Fe–N–O groups are again "linear" with an average angle of 165.8° (range 163.0–167.8°). Figure 2 shows one of the anions from the asymmetry unit.

Thus while none of the early formulations of the diiron structure (*5, 7*) proved to be correct, Seel's 1942 formulation of the structure of $[Fe_4S_3(NO)_7]^-$ (*8*), based upon the FeS structure, is remarkably close to the molecular structure found by X-ray analysis (*11, 39*).

B. $[Fe_2(SR)_2(NO)_4]$

When R is C_2H_5 or $HgCH_3$ the molecules are found to be centrosymmetric (*10, 31*), each having crystallographic C_i ($\bar{1}$) symmetry and approximate C_{2h} molecular symmetry. Thus of the two possible isomeric forms **3a** and **3b**, only the anti form **3b** is observed in the solid state for $[Fe_2(SEt)_2(NO)_4]$ and $[Fe_2(SHgCH_3)_2(NO)_4]$.

On the other hand, in $[Fe_2\{S_2Pt(PPh_3)_2\}(NO)_4]$, in which the two sulfurs of the Fe_2S_2 fragment are bonded to the same platinum, the structure necessarily has approximate C_{2v} rather than C_{2h} symmetry (*32*). Figures 3–5 show the molecular configuration of $[Fe_2(SEt)_2(NO)_4]$, $[Fe_2(SHgCH_3)_2(NO)_4]$, and $[Fe_2\{S_2Pt(PPh_3)_2\}(NO)_4]$, respectively.

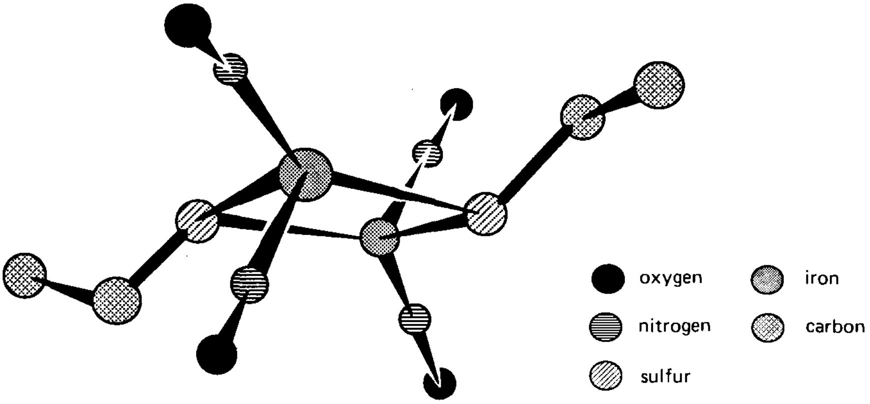


FIG. 3. The structure of $[Fe_2(SEt)_2(NO)_4]$. Redrawn from Ref. *10*.

The salient molecular dimensions for crystallographically characterized complexes $[Fe_2(SR)_2(NO)_4]$ are collected in Table I, together with those for $[Fe_2S_2(NO)_4]^{2-}$ (*59*). The important features are (1) the smaller size of the Fe_2S_2 fragment in $[Fe_2S_2(NO)_4]^{2-}$; (2) the folding of the Fe_2S_2 ring about the Fe–Fe vector, in $[Fe_2\{S_2Pt(PPh_3)_2\}(NO)_4]$, consequent upon the bridging by platinum of the two sulfurs; and (3) the existence in $[Fe_2\{S_2Pt(PPh_3)_2\}(NO)_4]$, of two distinct configurations of the Fe–N–O fragments. The Fe–N–O groups on the same side of the molecule as the platinum atom are "linear" (FeNO angle, 172.1°), while those on the opposite side are distinctly nonlinear, with an average

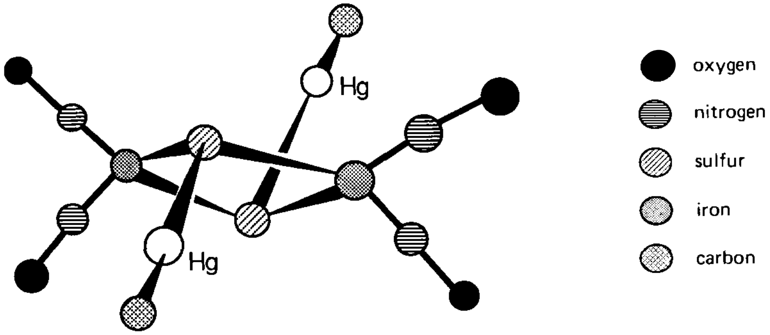


FIG. 4. The structure of $[Fe_2(SHgCH_3)_2(NO)_4]$. Redrawn from Ref. *31*.

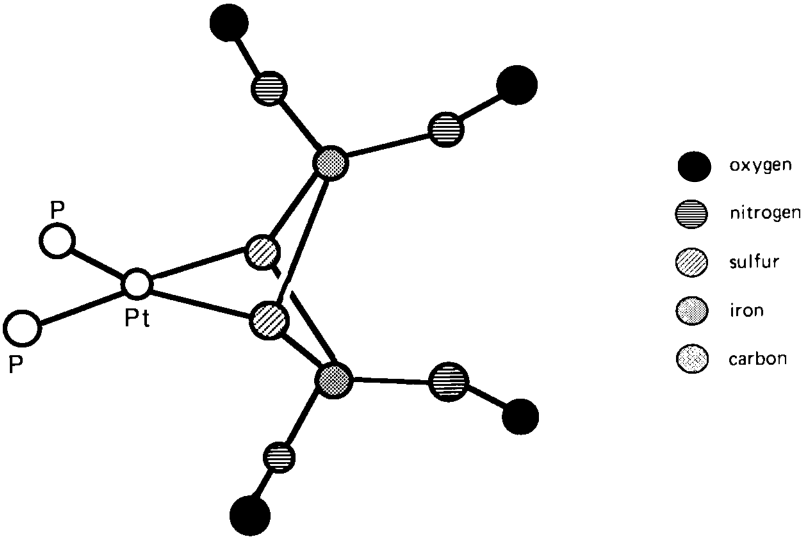


FIG. 5. The structure of $[Fe_2\{S_2Pt(PPh_3)_2\}(NO)_4]$. Redrawn from Ref. *32* (phenyl groups omitted).

FeNO angle of 150.3°. It has been suggested (*32*) that the bonding of the nitrosyls remote from platinum arises from the interaction of the nitrosyl π orbitals with the orbitals concentrated in the Fe–Fe bond, whose disposition in turn is determined by the puckering of the Fe_2S_2 ring; however, no theoretical support for this idea is yet available.

TABLE I

SELECTED GEOMETRIC PARAMETERS FOR $[Fe_2S_2(NO)_4]^{2-}$ AND $[Fe_2(SR)_2(NO)_4]$

Complex	Idealized molecular symmetry	*d*(Fe–S) (Å)[a]	*d*(Fe–Fe) (Å)	*d*(S···S) (Å)	(Fe–N–O) (degrees)[a]	Reference
$[Fe_2S_2(NO)_4]^{2-}$ [b]	D_{2h}	2.239	2.716	3.562	165.4	*59*
		2.249	2.713	3.587	166.2	*59*
$[Fe_2(SEt)_2(NO)_4]$	C_{2h}	2.270(4)	2.720(3)	3.63	167	*10*
$[Fe_2(SHgCH_3)_2(NO)_4]$	C_{2h}	2.275(7)	2.771(7)	3.607	166.5	*31*
$[Fe_2S\{SPt(PPh_3)_2\}(NO)_4]$	C_{2v}	2.275(5)	2.802(5)	3.241(7)	150.3 (trans)	*32*
					172.1 (cis)	*32*

[a] Averaged values.

[b] Two independent molecules in an asymmetric unit.

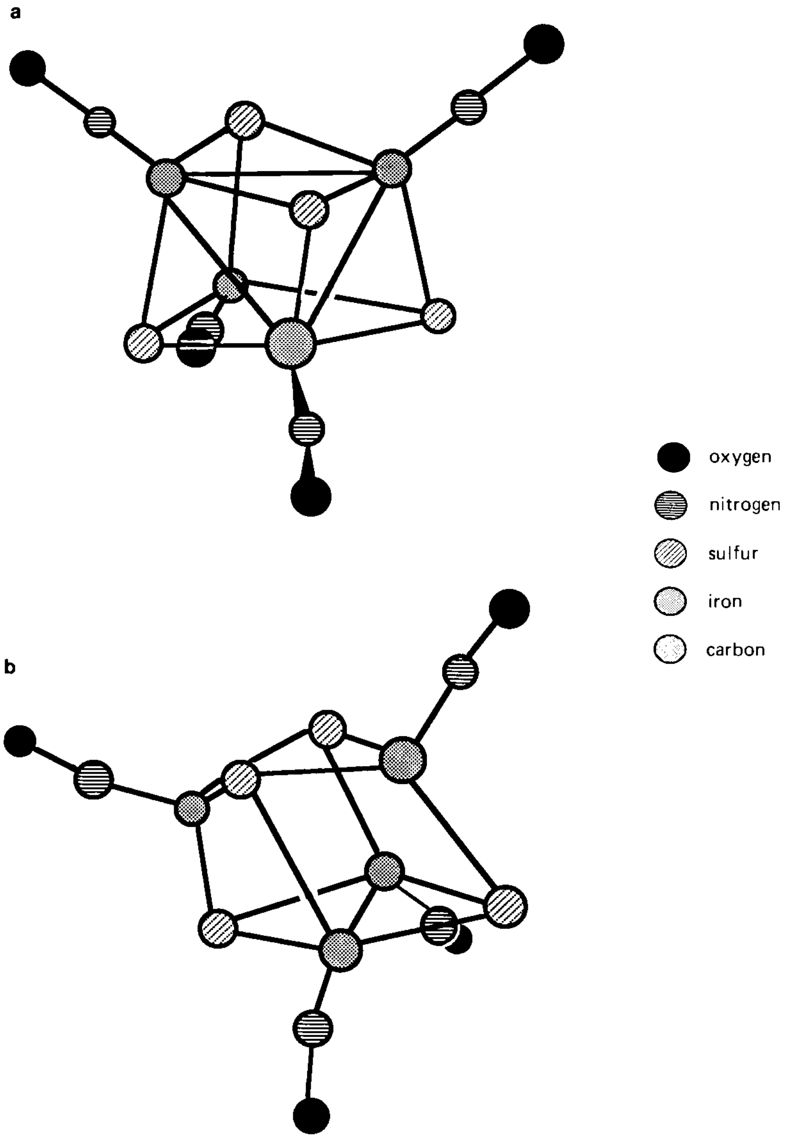


FIG. 6. The structure of (a) $[Fe_4S_4(NO)_4]$ and (b) $[Fe_4S_4(NO)_4]^-$. Both redrawn from Ref. *37*.

C. $[Fe_4S_4(NO)_4]$ AND RELATED CLUSTERS

The neutral cubane-like cluster $[Fe_4S_4(NO)_4]$ (4) has almost perfect tetrahedral T_d symmetry (*37*). The cluster has a tetrahedral Fe_4 core with Fe–Fe distances of 2.649 Å—slightly shorter than in $[Fe_4S_3(NO)_7]^-$ and $[Fe_2(SR)_2(NO)_4]$—with each face of the tetrahedron triply bridged by sulfur, such that Fe—S is 2.217 Å and S---S is 3.503 Å, again both shorter than found for $[Fe_2(SR)_2(NO)_4]$. Because of the difference between the Fe—Fe distance and the S---S distance, it is perhaps better to think of this structure as based upon two intersecting tetrahedra rather than a cube. As usual the Fe–N–O groups are linear, with an average angle of 177.6°. The structure is shown in Fig. 6a.

Addition of a single electron to $[Fe_4S_4(NO)_4]$, of T_d symmetry, to provide $[Fe_4S_4(NO)_4]^-$, causes a reduction in symmetry to D_{2d} in the $[K(2,2,2\text{-crypt})]^+$ salt (*37*). In the anion, Fig. 6b, there are two distinct types of Fe–Fe bond, of length 2.704 (twofold) and 2.688 Å (fourfold), indicative of an Fe_4 core which is not only reduced in symmetry, but increased in size compared with that in neutral $[Fe_4S_4(NO)_4]$. The Fe–S distances are also slightly larger in the anion, 2.231 Å, than in the neutral cluster, 2.217 Å, although the S---S distances, 3.496 (twofold) and 3.517 Å (fourfold), are very little different from the 3.503 Å in the neutral complex. From this comparison the following may be deduced (*37*) concerning the electronic structure: the lowest unoccupied molecular orbital (LUMO) in $[Fe_4S_4(NO)_4]$ and the semioccupied molecular orbital (SOMO) in $[Fe_4S_4(NO)_4]^-$ (1) are localized primarily in the Fe_4 cage; (2) are antibonding in character; and (3) are degenerate (e or t_1 or t_2), assuming that the change of symmetry upon reduction is due to the Jahn–Teller effect.

The related complexes $[Fe_4S_2(NO)_4(NCMe_3)_2]$ and $[Fe_4S_2(NO)_4(NCMe_3)_2]^-$, Fig. 7, each have C_{2v} symmetry in the solid state (*41*); a detailed comparison of the $Fe_4S_2N_2$ core geometry in neutral and anionic forms shows (*41*) that the LUMO in $[Fe_4S_2(NO)_4(NCMe_3)_2]$ and the SOMO in $[Fe_4S_2(NO)_4]\ (NCMe_3)_2]^-$ are localized in the Fe_4 cage, as for $[Fe_4S_4(NO)_4]$ and its anion (*37*) with Fe–Fe antibonding character localized primarily in the unique Fe_2S_2 and Fe_2N_2 faces, rather than in the fourfold Fe_2SN faces.

D. $[Fe(NO)(S_2CNR_2)_2]$ AND RELATED COMPLEXES

The complexes $[Fe(NO)(S_2CNMe_2)_2]$ (*60*), Fig. 8, and $[Fe(NO)(S_2CNEt_2)_2]$ (*61*) both have square–pyramidal geometry with a linear, apical, Fe–N–O group. The nitrogen(IV) oxide oxidation product

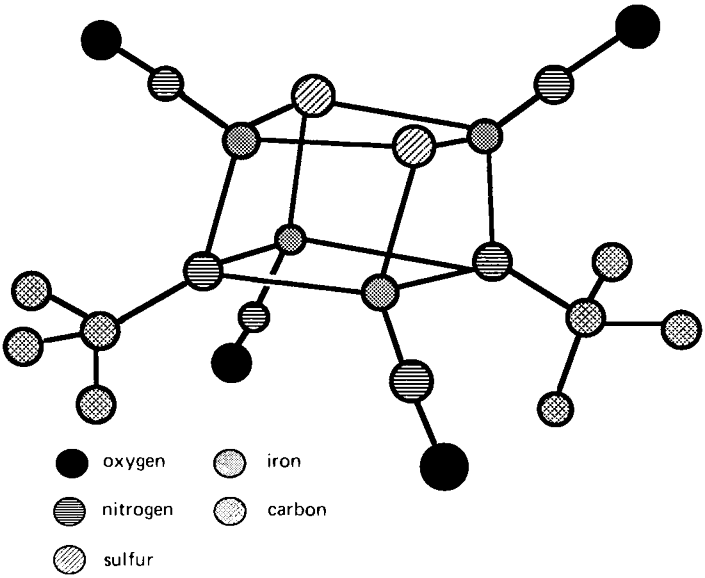


FIG. 7. The structure of $[Fe_4S_2(NO)_4(NCMe_3)]$. Redrawn from Ref. *41*.

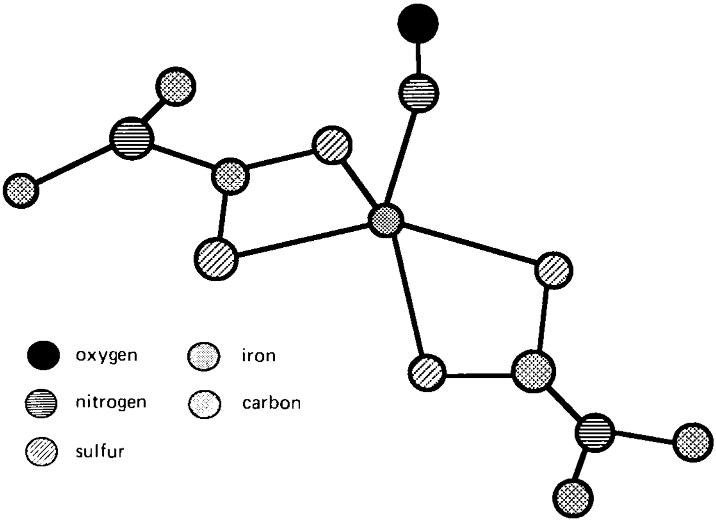


FIG. 8. The structure of $[Fe(NO)(S_2CNMe_2)_2]$. Redrawn from Ref. *60*.

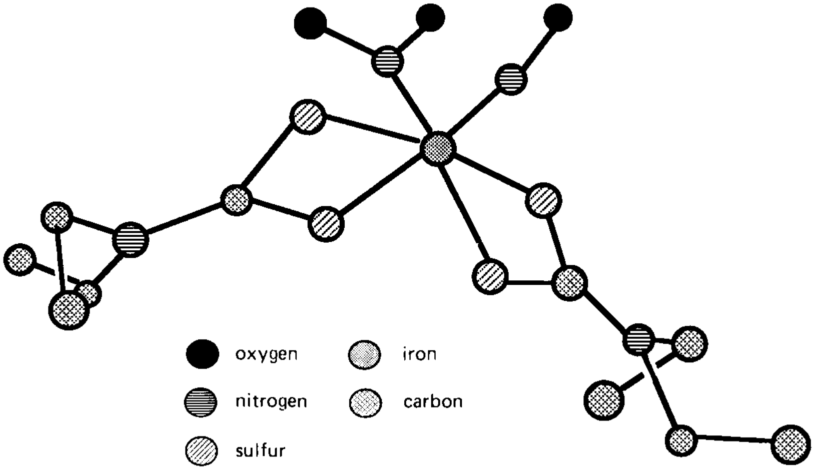


FIG. 9. The structure of *cis*-[Fe(NO)(NO$_2$)(S$_2$CNEt$_2$)$_2$]. Redrawn from Ref. *62*.

from [Fe(NO)(S$_2$CNEt$_2$)$_2$] (*46, 47*) has been shown (*62*) to be *cis*-[Fe(NO)(NO$_2$)(S$_2$CNEt$_2$)$_2$], Fig. 9, again with a linear iron–nitrosyl fragment. The dithiocarbamate complex **6** also has a "linear" Fe–N–O fragment (*48*).

In complexes **9** and **10**, the Fe–N–O groups are distinctly bent (*49, 51*) although the nitrosyl ligand still occupies the apical site in an approximately square–pyramidal complex. Complex **9** crystallizes with two independent molecules in the asymmetric unit for which the bond angles Fe–N–O are 155.2(5) and 158.4(5)°, respectively (**49**), Fig. 10a, while in complex **10** the angle is (*51*) 155.2(9)°, Fig. 10b. The values of the Fe–N–O angle in complexes **9** and **10** are thus very similar to those of the trans nitrosyl ligands in [Fe$_2${S$_2$Pt(PPh$_3$)$_2$}(NO)$_4$] (*32*).

In the closely related complex **11**, the four-coordinate iron adopts nearly regular tetrahedral geometry with "linear" iron–nitrosyl groups (*51*), Fig. 11.

E. SELENIUM AND TELLURIUM ANALOGS

The iron–selenium cubane-type cluster [Fe$_4$Se$_4$(NO)$_4$] has been shown (*52*) to adopt a molecular structure of almost exact T_d symmetry, whereas in the corresponding anion [Fe$_4$Se$_4$(NO)$_4$]$^-$ the symmetry is lowered to D_{2d}, just as for the sulfur analogs (*37*). Upon one-electron reduction the size of the Fe$_4$ cage increases: in the neutral molecule the Fe–Fe and Fe–Se distances are 2.703 and 2.342 Å, but in the anion the

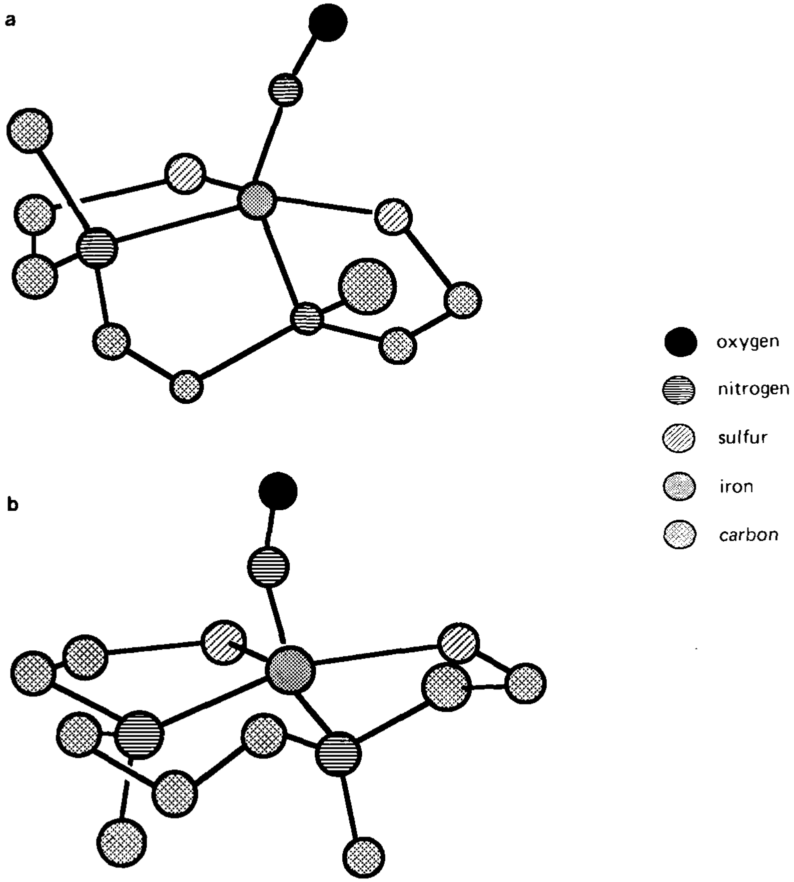


FIG. 10. The structure of (a) complex **9** and (b) complex **10**. Redrawn from Refs. *49* and *51*, respectively.

Fe–Fe distances are increased to 2.770 (twofold) and 2.75 Å (fourfold), while the Fe–Se distances are all 2.354 Å: the Se ···· Se distances are scarcely affected, so that, as before, the LUMO in $[Fe_4Se_4(NO)_4]$ and the SOMO in $[Fe_4Se_4(NO)_4]^-$ are antibonding and localized primarily in the Fe_4 cage.

The triphenylphosphine complex $[Fe_4Se_3(NO)_4(PPh_3)_3]$ (**12**) has (*52*) a structure which resembles that of $[Fe_4S_3(NO)_7]^-$ (*11, 39*) in which the equatorial nitrosyl ligands on the basal iron are replaced by triphenylphosphine ligands. However, the molecular symmetry is reduced from C_{3v} to C_s, and the basal Fe_3 triangle contains one Fe–Fe distance of 2.695 and two of 2.845 Å. The structure of $[Fe_4Se_3(NO)_7]^-$

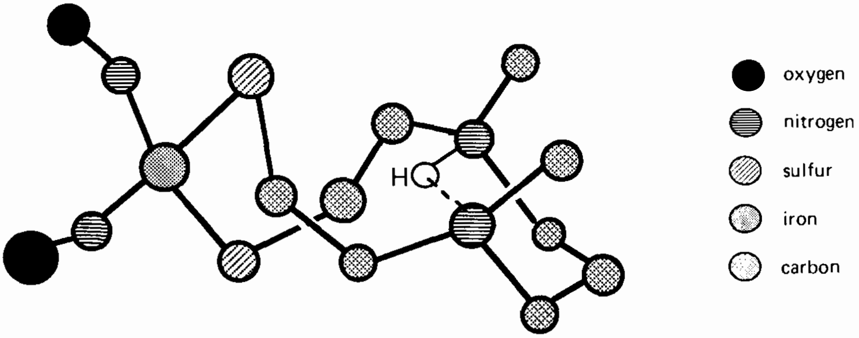


FIG. 11. The structure of complex **11**. Redrawn from Ref. *51*.

appears not to have been determined, but by analogy with $[Fe_4S_3(NO)_7]^-$, C_{3v} symmetry is to be expected. In the dianion $[Fe_4Se_3(NO)_7]^{2-}$, however, the symmetry is not C_{3v} but C_s (*52*). suggesting that the LUMO in $[Fe_4Se_3(NO)_7]^-$ is of a type giving a Jahn–Teller distortion upon reduction. In the basal Fe_3 triangle of $[Fe_4Se_3(NO)_7]^{2-}$ the unique Fe–Fe distance is 3.637 Å, the others 3.750 Å, a difference of magnitude comparable to that in $[Fe_4Se_3(NO)_4(PPh_3)_3]$, although the distances themselves are very much greater. In all of these selenium complexes, the Fe–N–O fragments are linear. The only iron–tellurium–nitrosyl complex which has so far been characterized by X-ray crystallography is $[Fe_2(TePh)_2(NO)_4]$ (*52*): this complex is centrosymmetric, i.e., analogous to structure **3b** with "linear" Fe–N–O groups, and an Fe–Fe distance of 2.801 Å, very little longer than in $[Fe_2(SR)_2(NO)_4]$ complexes (Table I).

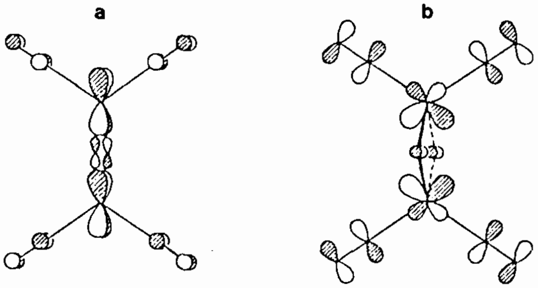


FIG. 12. Frontier orbitals in $[Fe_2(SH)_2(NO)_4]$ (a) LUMO (B_g) and (b) HOMO (B_u). Reproduced with permission from *Inorg. Chem.* **24**, 3858 (1985).

F. HETEROMETALLIC IRON–SULFUR–NITROSYLS

The structure of the heterometallic complexes **14**, **17**, **18**, and **19** have all been established by X-ray crystallography, (*26, 54, 56*). The principal points of interest arising from these studies, aside from the definitive establishment of the constitutions of these complexes, are as follows: (1) all the Fe–N–O groups are linear and (2) complex **17** adopts (*26*) the syn configuration analogous to **3a**, with both phenyl groups on the side of the FeS_2Co ring remote from the triphenylphosphine, and it is presumably the repulsive steric interaction between the several phenyl groups which distinguish the configuration of structure **17** from those of $[Fe_2(SR)_2(NO)_4]$ complexes (Section II,G).

IV. Molecular Structure: NMR Spectroscopy

A. ^1H NMR SPECTROSCOPY OF $[Fe_2(SR)_2(NO)_4]$

The ^1H NMR spectra of solutions of $[Fe_2(SR)_2(NO)_4]$ is noncoordinating solvents for a wide range of organic substituents R [R = Me, Et, *n*-Pr, *i*-Pr, *n*-Bu, *i*-Bu, *t*-Bu, *n*-C_5H_{11}, $CH_2{=}CHCH_2$, $HC{\equiv}CCH_2$, $CH_3C(O)CH_2$, Me_3SiCH_2, Ph, and $PhCH_2$] show (*27, 30, 63, 64*) the presence of two isomeric forms: these spectra have been interpreted in terms of the forms **3a** and **3b**, although the ^1H spectra do not establish these forms. For all substituents except R = *t*-Bu, the two isomers are present in virtually equal abundance, implying that in solution the ΔG_f^0 values are esentially identical. When R = *t*-Bu (*64*), the isomer ratio is 1:3 in favor of the syn isomer **3a** (rigorously established by use of ^{15}N NMR; see below). The existence of two forms has been confirmed by ^{13}C NMR in a number of cases (*27, 63*).

B. ^{15}N NMR SPECTROSCOPY OF $[Fe_2(SR)_2(NO)_4]$

The ^{15}N spectra of a number of complexes $[Fe_2(SR)_2(^{15}NO)_4]$ enriched to 99% in ^{15}N, have been studied in noncoordinating solvents (*25, 63, 64*). In every case the spectrum comprises a singlet and a pair of doublets: the singlet is assigned to the anti isomer **3b** and the two doublets, which comprise an AX system, to the syn isomer **3a**. In **3b** all the nitrosyl ligands are equivalent in C_{2h} symmetry, while in **3a**, although the two irons are equivalent and the two substituents R are also equivalent, the two nitrosyl ligands in each $Fe(^{15}NO)_2$ group are nonequivalent and the coupling $^2J(^{15}NFe^{15}N)$ between the ^{15}N nuclei yields the observed AX spectra. No molecular symmetries for **3a** and **3b** other than C_{2v} and C_{2h}, respectively, can yield the observed ^{15}N spectra. Except when R = *t*-Bu, the spectra show the two isomers to be of equal abundance: if R = *t*-Bu, the C_{2v} isomer dominates and the isomer ratio is constant at 2.85 throughout the temperature range 220–298 K: this implies that for the syn $\rightleftharpoons$ anti equilibrium, ΔH^0 is zero and ΔS^0 is 8.7 J K^{-1} mol^{-1}. One possible explanation (*64*) for the behavior of $[Fe_2(SBu\text{-}t)_2(NO)_4]$ lies in differential specific solvation of the two forms: specific solvation was invoked (*65*) to rationalize some of the solvent shift properties of the ^1H spectrum of $[Fe_2(SMe)_2(NO)_4]$, where the overall behavior was satisfactorily correlated with Taft's solvatochromic parameter, π^* (*66, 67*). The existence in solution of two forms corresponding to structures **3a** and **3b** for such a wide range of substituents is remarkable in view of the fact that only isomer **3b** has been observed in the solid state (see Section III,B).

As expected, the ^{15}N spectrum of $[Fe_2S_2(^{15}NO)_4]^{2-}$ consists of a singlet, as all the nitrosyl ligands are equivalent (*63*). However, in methylene chloride solution, $[Fe_2S_2(NO)_4]^{2-}$ is rapidly and cleanly converted to $[Fe_4S_3(NO)_7]^-$, which is then the sole species detectable in solution using ^{15}N NMR (*25, 63*); and by-products remain uncharacterized.

For each complex $[Fe_2(SR)_2(NO)_4]$ examined, the ^{15}N chemical shift is in the range characteristic (*68–70*) of linear M–N–O groups.

C. ^{15}N NMR SPECTROSCOPY OF TETRAIRON COMPLEXES

The ^{15}N NMR of $[Fe_4S_3(^{15}NO)_7]^-$ (99% ^{15}N) consists of a singlet and a pair of doublets (*25*); the relative intensities allow the assignment of the singlet to the apical nitrosyl group and the two doublets, which comprise an AX system, to the axial and equatorial nitrosyl ligands on the basal irons. Since the two ligands in each basal $Fe(NO)_2$ fragment are distinct, the coupling $^2J(^{15}NFe^{15}N)$ is observed. The spectrum shows that $[Fe_4S_3(NO)_7]^-$ retains its structure in solution. The spectrum of $[Fe_4Se_3(^{15}NO)_7]^-$, which has not yet been characterized by X-ray crystallography, is very similar to that of $[Fe_4S_3(^{15}NO)_7]^-$; this and the observation of only a single ^{77}Se resonance (*25*) show that $[Fe_4Se_3(NO)_7]^-$ also has C_{3v} symmetry in solution.

Each of $[Fe_4X_4(^{15}NO)_4]$ (99% ^{15}N; X = S or Se) exhibits a singlet only in its ^{15}N NMR spectrum in CD_2Cl_2 solution, demonstrating structural similarity and structural integrity in solution in this solvent.

All of the tetrairon complexes have ^{15}N chemical shifts characteristic of linear Fe–N–O groups.

V. Electronic Structure

A. OXIDATION STATES

Bulk susceptibility measurements (*6*) and the observation of sharp, unshifted resonances in the NMR spectra of both diiron and tetrairon complexes, and of cosolutes (*37*), show that $[Fe_2S_2(NO)_4]^{2-}$ and all $[Fe_2(SR)_2(NO)_4]$, $[Fe_4X_3(NO)_7]^-$, and $[Fe_4X_4(NO)_4]$ ($X = S$ or Se) species are diamagnetic. On the other hand, the mononuclear complexes **5** (*18, 23*), **9** and **10** (*49*), and **11** (*51*) are all paramagnetic, each containing a single unpaired electron per molecular unit. Likewise, $[Fe_4S_4(NO)_4]^-$ (*37*) and $[Fe_4Se_3(NO)_4(PPh_3)_3]$ (*52*) are paramagnetic, containing, respectively, one and probably two unpaired electrons per molecular unit.

Furthermore, Mössbauer spectroscopy has shown that the two iron atoms in $[Fe_2S_2(NO)_4]^{2-}$ are equivalent (*71*), and that the four sites in each of $[Fe_4S_4(NO)_4]$ (*72*) and $[Fe_4S_4(NO)_4]^-$ (*37*) are equivalent, as expected from the observed (*37*) T_d and D_{2d} molecular symmetries. However, Mössbauer studies of isomorphous alkali metal or ammonium $[Fe_4S_3(NO)_7]^-$ salts have provided contradictory conclusions; two studies (*72, 73*) concluded that the spectrum contained only a single quadrupole doublet, despite the clear crystallographic demonstration (*11, 39*) of two quite different iron environments (cf. Fig. 1), while in two further studies (*71, 74*) the spectra were interpreted in terms of two iron sites whose relative populations were refined as 2.85:1 (*71*) and 3.03:1 (*74*). It is probably best to conclude that the two geometrically different iron types in $[Fe_4S_3(NO)_7]^-$ are in similar electronic environments. Likewise, the two geometrically distinct iron types in $[Fe_4S_2(NO)_4(NCMe_3)_2]$ (*41*) are in very similar electronic environments, as this compound also gives a Mössbauer spectrum containing only a single quadrupole doublet (*72*). For each of $NH_4[Fe_4S_3(NO)_7]$, $[Fe_4S_4(NO)_4]$, and $[Fe_4S_2(NO)_4(NCMe_3)_2]$, the Mössbauer spectra are indicative of diamagnetic ground states (*72*), consistent with bulk susceptibility and NMR data.

Since in all iron–sulfur–nitrosyl complexes hitherto characterized by either X-ray crystallography or ^{15}N NMR spectroscopy, the Fe–N–O fragments are approximately linear, the nitrosyl ligands are considered to be bound formally as NO^+. This then implies that the formal oxidation state of the iron atoms in $[Fe_2S_2(NO)_4]^{2-}$ and in $[Fe_2(SR)_2(NO)_4]$ is Fe(−I), d^9; in $[Fe_4S_4(NO)_4]$ and $[Fe_4S_2(NO)_4(NCMe_3)_2]$ it is Fe(I), d^7, while in $[Fe_4S_3(NO)_7]^-$ the apical iron is formally Fe(I) and the three basal irons are formally Fe(−I). In the paramagnetic mononuclear complexes **5**, **9**, **10**, and

16, the $\{Fe(NO)\}^7$ (*18*) fragments contain formally Fe(I), while in complexes **11** and **15**, the $\{Fe(NO)_2\}^9$ fragments contain formally Fe(–I).

Adoption of the oxidation state Fe(–I) for $Fe(NO)_2$ fragments leads to the assignment of Co(O) in the binuclear heterometallic complex **17**, $[(ON)_2Fe(SPh)_2Co(NO)(PPh_3)]$, while adoption of Fe(I) for the Fe(NO) fragments in the heterometallic cubane **19** leads to a formal oxidation state V(III) for vanadium.

The diamagnetic behavior of the diiron and tetrairon complexes, despite the presence of formally d^7 and/or d^9 iron centers, indicates very strong coupling between the individual paramagnetic centers: all theoretical treatments of polynuclear iron–sulfur–nitrosyl complexes to date have been based on the assumption of diamagnetism in even-electron species and have employed molecular orbital methods at various levels of approximation.

B. DINUCLEAR COMPLEXES

Extended Hückel molecular orbital (EHMO) calculations on $[Fe_2S_2(NO)_4]^{2-}$ and $[Fe_2(SH)_2(NO)_4]$, using geometries derived from that found for $[Fe_2(SEt)_2(NO)_4]$ by X-ray analysis, showed (*75*) that the frontier orbitals are concentrated in the Fe–Fe bond in each case, with the HOMO bonding and the LUMO antibonding in the Fe–Fe bond. The frontier orbitals in *anti*-$[Fe_2(SH)_2(NO)_4]$ are shown in Fig. 12. The electron-precise nature of the Fe–Fe interaction suggests that both electron addition to and electron removal from $[Fe_2(SR)_2(NO)_4]$ will weaken the Fe–Fe bond, possibly leading to cleavage into mononuclear fragments. It is noteworthy in this connection that the stoichiometrically analogous cobalt complexes $[Co_2(SR)_2(NO)_4]$, in which there is an extra pair of electrons compared with $[Fe_2(SR)_2(NO)_4]$ and which lack a metal–metal bond, are much more reactive than the iron complexes and very readily form mononuclear complexes (*26*). Thus $[Co_2(SPh)_2(NO)_4]$ reacted with triphenylphosphine to give an 88% yield of mononuclear $[Co(NO)_2(SPh)(PPh_3)]$, in 15 minutes at room temperature, while $[Fe_2(SPh)_2(NO)_4]$ gave a 50% yield of $[Fe(NO)_2(PPh_3)_2]$ only after reaction for 3 days (*26*).

The complexes $[Fe_2(SR)_2(NO)_4]$ contain a total of 34 valence electrons and are isoelectronic with $[Fe_2(SR)_2(CO)_6]$ and with $[Fe_2(CO)_9]$; with a single Fe–Fe bond, each obeys the 18-electron rule. The cobalt complexes $[Co_2(SR)_2(NO)_4]$, on the other hand, contain 36 valence electrons and thus obey the 18-electron rule in the absence of any metal–metal bond, while the heterometallic complex **17** is another 34-electron species containing a Co–Fe bond.

C. TETRANUCLEAR COMPLEXES

In both $[Fe_4X_4(NO)_4]$($X = S$ or Se) and $[Fe_4S_2(NO)_4(NCMe_3)_2]$ the total valence electron count is 60. This is the number characteristic of tetrahedral tetranuclear metal clusters, such as $[Ir_4(CO)_{12}]$, in the Wade and Mingos skeletal-electron counting schemes (*76, 77*) and, furthermore, each iron atom in these clusters obeys the 18-electron rule, provided that it forms single Fe–Fe bonds to each of the other iron atoms in the tetrahedron.

However, the counting schemes which have proved to be so valuable in the rationalization of stoichiometry and structure in both metal–carbonyl clusters and posttransition metal clusters cannot play more than a marginal role for metal–sulfur–nitrosyl systems, since the total valence electron counts in currently known Fe_4 and related systems range between 54 and 72; thus, for example, $[Fe_4S_4(SR)_4]^{2-}$ (*78, 79*) has a total valence electron count of 54, $[Fe_4S_4(NO)_4]$ and $[Fe_4S_2(NO)_4(NCMe_3)_2]$ have 60, $[Fe_4Se_3(NO)_4(PPh_3)_3]$ (*52*) has 62, $[Fe_4S_3(NO)_7]^-$ has 66, $[Fe_4S_4(\eta^5\text{-}C_5H_5)_4]$ (*80*) has 68, and $[Fe_4S_4(CO)_{12}]$ (*81*) has 72. Among heterometallic M_4 systems, complexes **19** and **21** (*26, 56*) have 58 and 59 valence electrons, respectively. In addition, many stoichiometries occur in a range of oxidation states, for example, $[Fe_4S_4(SR)_4]^{2-/3-}$ (*78, 79, 82, 83*), $[Fe_4S_4(NO)_4]^{0/1-/2-}$ (*37*), $[Fe_4S_2(NO)_4(NCMe_3)_2]^{0/1-}$ (*41*), $[Fe_4S_4(\eta^5\text{-}C_5H_5)_4]^{1-/0/1+/2+/3+}$ (*80, 84, 85*), $[(\eta^5\text{-}C_5H_4CH_3)_2V_2Fe_2S_4(NO)_2]^{0/1-/2-}$ (*26*), and $[(\eta^5\text{-}C_5H_4CH_3)_2V_2FeCoS_4(NO)_2]^{0/1-/2-}$ (*26*). In virtually all of the complexes of type $L_4M_4X_4$, the M_4X_4 core has either T_d or D_{2d} symmetry, regardless of the valence electron count, and hence these systems must be regarded as outside the scope of Wade's rules.

In tackling problems of molecular and electronic structure such as those posed by these sulfur-bridged tetrametallic clusters, two approaches are possible. One is the construction, often heavily reliant upon symmetry arguments, of a general, essentially qualitative model intended to provide a broad description of a series of molecules; the other is a detailed quantum mechanical study, at an appropriate level of theory, of individual molecules, followed by a search for generalization or patterns. A combination of both approaches is usually the most valuable for chemical understanding, and much effort along these lines has been expanded on cubane-type clusters and their derivatives.

Dahl has employed (*37, 85*) a qualitative molecular orbital model for $[Fe_4S_4L_4]$ complexes based on T_d symmetry, the essential features of which are summarized in Fig. 13. The 20 iron *d* orbitals form molecular orbitals which can be divided into three major groups. The first group,

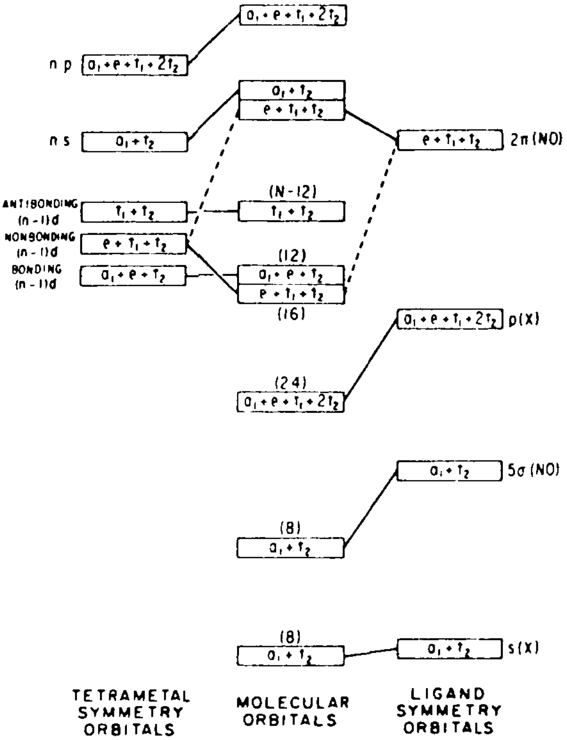


FIG. 13. Qualitative molecular orbital scheme for $[Fe_4S_4L_4]$. Complexes of T_d symmetry. Reproduced with permission from *J. Am. Chem. Soc.* **104**, 3409 (1982).

of 8 orbitals of symmetry types ($e + t_1 + t_2$), is primarily involved in π bonding with ligands L, and is essentially nonbonding in the Fe_4 cage; the second group, 6 orbitals of types ($a_1 + e + t_2$), is bonding in the Fe_4 cage; and the third group, also of 6 orbitals, of symmetry types ($t_1 + t_2$), is antibonding in the Fe_4 cage. While the Fe_4 antibonding orbitals are the highest in energy, the model retains some flexibility in the ordering of the bonding and nonbonding sets, dependent upon the pendant ligands L.

Table II shows the distribution of electrons among the molecular orbitals for a range of representative Fe_4S_4 complexes. According to this scheme, both $[Fe_4S_4(NO)_4]$ and $[Fe_4S_4(CO)_{12}]$ have closed-shell configurations, and hence should show exact T_d symmetry, as observed (*37, 81*); on the other hand, in T_d symmetry, both $[Fe_4S_4(SR)_4]^{2-}$ and $[Fe_4S_4(\eta^5\text{-}C_5H_5)_4]$ have open-shell configuration, and hence are expected, via the Jahn–Teller effect, to undergo a lowering of

TABLE II

ELECTRON DISTRIBUTIONS IN REPRESENTATIVE Fe_4S_4 COMPLEXES UNDER ASSUMED T_d SYMMETRY

Orbitals	$[Fe_4S_4(SR)_4]^{2-}$	$[Fe_4S_4(NO)_4]$	$[Fe_4S_4(\eta^5\text{-}C_5H_5)_4]$	$[Fe_4S_4(CO)_{12}]$
Fe_4 antibonding $(t_1 + t_2)$	0	0	8	12
Fe_4 nonbonding $(e + t_1 + t_2)$	10	16	16	16
Fe_4 bonding $(a_1 + e + t_2)$	12	12	12	12
Fe–X $(a_1 + e + t_1 + 2t_2)$	24	24	24	24
Fe–L $(a_1 + t_2)$	8	8	8	8
Total valence electrons	54	60	68	72

their symmetry, again exactly as observed (*78–80*). Reduction of $[Fe_4S_4(NO)_4]$ to $[Fe_4S_4(NO)_4]^-$ yields an open-shell species, which according to this scheme is Jahn–Teller sensitive; the observed (*37*) structure for $[Fe_4S_4(NO)_4]^-$ has D_{2d} symmetry, as do $[Fe_4S_4(SR)_4]^{2-}$ (*78, 79*) and $[Fe_4S_4(\eta^5\text{-}C_5H_5)_4]$ (*80*). Furthermore, this model neatly rationalizes the steady increase in the Fe–Fe distances as the number of Fe_4 antibonding electrons increases from zero in $[Fe_4S_4(NO)_4]$ (*37*) to six in $[Fe_4S_4(\eta^5\text{-}C_5H_5)_4]^{2+}$ (*85*), seven in $[Fe_4S_4(\eta^5\text{-}C_5H_5)_4]^+$ (*84*), and eight in neutral $[Fe_4S_4(\eta^5\text{-}C_5H_5)_4]$ (*80*).

According to Dahl's model (*37*), $[Fe_4S_4(NO)_4]$ with 60 valence electrons has 12 electrons which are bonding in the Fe_4 cage, equivalent to six single Fe–Fe bonds, one along each edge of the cage. In the 66-electron anion $[Fe_4S_3(NO)_7]^-$ (*39*), application of the same basic model with the overall symmetry lowered from T_d to C_{3v} provides a Fe_4 cage having 12 bonding and 6 antibonding electrons, equivalent to a total Fe_4 bond order of 3, or a single Fe–Fe bond along only three edges of the Fe_4 cage; experimentally (*39*), there are three Fe–Fe distances of 2.70 Å (bonds) between apical and basal irons and three of 3.57 Å (nonbonds) between pairs of basal irons.

Quantitative calculations (*75*) on $[Fe_4S_4(NO)_4]$ using the extended Hückel molecular orbital (EHMO) method have provided results in broad agreement with the Dahl scheme (*37*) (cf. Fig. 13 and Table II): the 4 molecular orbitals arising from the NO orbitals lie at −15.61 (a_1) and −15.54 (t_2) eV; the 12 Fe–S orbitals are grouped between −15.30 and −14.31 eV; and the 14 occupied Fe–Fe orbitals are grouped between −13.28 and −11.41 eV. However, the orbitals which are, respectively, bonding or nonbonding for the Fe_4 cage are not found in separate energy regions, but are interleaved. The highest occupied molecular orbital (HOMO) of t_2 type is nonbonding in Fe_4, while the

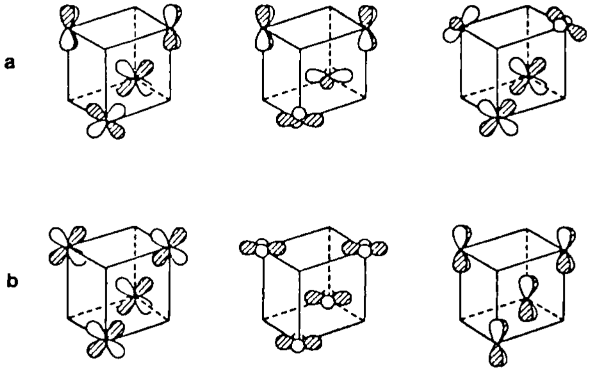


FIG. 14. Principal contributing orbitals to the (a) LUMO (T_1) and (b) HOMO (T_2) of $[Fe_4S_4(NO)_4]$. Reproduced with permission from *Inorg. Chem.* **24**, 3858 (1985).

LUMO of t_1 type is antibonding in Fe_4; the principal components of these orbitals are shown in Fig. 14. Thus addition of electrons to $[Fe_4S_4(NO)_4]$ should weaken the cluster bonding, as observed (*37*), but removal of one or two electrons should not seriously influence the cluster bonding. Similar calculations on $[Fe_4S_3(NO)_7]^-$ show a broadly similar order of the molecular orbitals, with the uppermost 17 occupied orbitals concentrated in the Fe_4 cage. Here bonding, nonbonding, and antibonding orbitals are all interleaved: the HOMO is a bonding Fe_4 orbital of a_1 type and the LUMO an antibonding Fe_4 orbital e type; the main components of these orbitals are shown in Fig. 15. Of the 17 occupied Fe_4 orbitals, 7 are bonding, 6 nonbonding, and 4 antibonding, giving a total net Fe_4 bond order of 3, essentially as required by the Dahl model (*37*). Since the HOMO and LUMO in $[Fe_4S_3(NO)_7]^-$ are, respectively, bonding and antibonding in Fe_4, either addition or subtraction of an electron is expected to weaken the cage bonding.

Both $[Fe_4S_4(NO)_4]$ and $[Fe_4S_3(NO)_7]^-$ were calculated (*75*) to have degenerate LUMOs of t_1 and e symmetry, respectively, so that Jahn–Teller ions are expected to result, in each case, from addition of an electron. In $[Fe_4S_3(NO)_7]^{2-}$, the system must distort along an e vibrational mode to give a product of C_s symmetry [cf. $[Fe_4Se_3(NO)_7]^{2-}$ (*52*)], while in $[Fe_4S_4(NO)_4]^-$ the system distorts either along an e mode to give a product of D_{2d} symmetry [as observed (*37*)], or along a t_2 mode to give a product of C_{3v} symmetry.

The electronic structures of the related complexes $[(\eta^5\text{-}C_5H_5)_4M_4X_4]$ have been discussed by Bottomley (*86*).

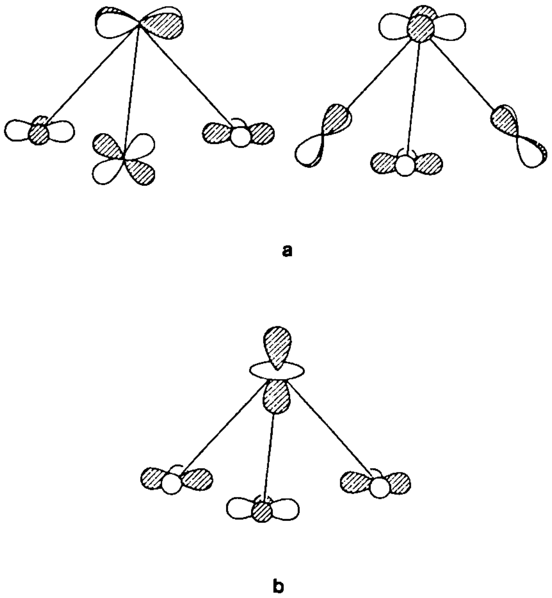


FIG. 15. Principal contributing orbitals to the (a) LUMO (E) and (b) HOMO (A_1) of $[Fe_4S_3(NO)_7]^-$. Reproduced with permission from *Inorg. Chem.* **24**, 3858 (1985).

D. MONONUCLEAR COMPLEXES

For the paramagnetic monoiron complexes **5** (R = Me) and **16**, having approximately square-pyramidal coordination of iron, EHMO calculations have shown (*55*) that the SOMO is of σ symmetry, directed along the Fe–N–O vector (Fig. 16a): this appears to be generally so for square–pyramidal iron- and nitrosyl-containing $\{Fe(NO)\}^7$ fragments, including also $[Fe(NO)(SH)_4]^{2-}$ (*55*) and $[Fe(CN)_4NO]^{2-}$ (*87*). On the other hand, in paramagnetic dinitrosyliron complexes of the general type $[Fe(NO)_2X_2]$, containing $\{Fe(NO)_2\}^9$ fragments, the SOMO is (*55*) of π symmetry with respect to the iron–nitrosyl directions (Fig. 16b). For linear Fe–N–O fragments with the nitrosyl ligand bound as NO^+, the tetrahedral $\{Fe(NO)_2\}^9$ complexes contain d^9 Fe(−I) and therefore have $S = \frac{1}{2}$ ground states. The square–pyramidal $\{Fe(NO)\}^7$ species contain d^7 Fe(I), but the d electron configuration $(e)^4(b_2)^2(a_1)^1(b_1)^0$ in approximate C_{4v} symmetry ensures spin pairing and hence an $S = \frac{1}{2}$ ground state.

The importance of the different nodal properties of the two types of SOMO shown in Fig. 16 lies in their influence upon the nitrogen hyperfine coupling $A(^{14}N)$ in the electron spin resonance spectra in

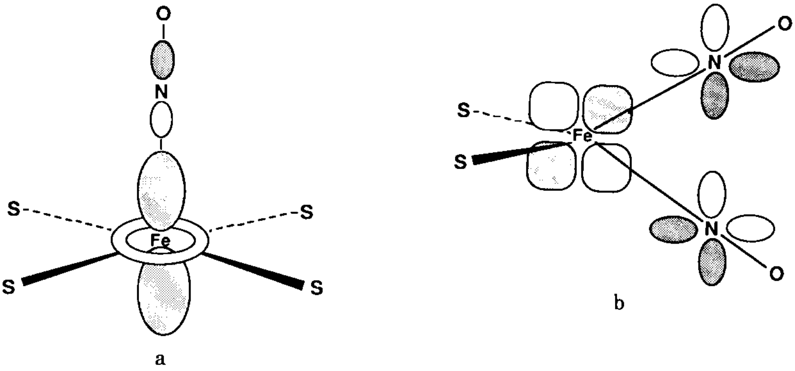


FIG. 16. Principal contributing orbitals to the SOMO in (a) square-pyramidal $\{Fe(NO)\}^7$ complexes and (b) tetrahedral $\{Fe(NO)_2\}^9$ complexes.

paramagnetic monoiron complexes. Those complexes having a σ SOMO of the type shown in Fig. 16a have $A(^{14}N)$ values in the range 12–15 G, while those having a π SOMO as shown in Fig. 16b have $A(^{14}N)$ values in the range 2–6 G (*23, 55, 87*). Hence the ESR spectra of paramagnetic monoiron–nitrosyl complexes give immediate information on the electronic structure, provided only that $A(^{14}N)$ can be resolved. Thus, for example, the complexes **9** and **10** each have an ESR spectrum with $A(^{14}N)$ of 12 G (*49, 51*), indicative of a σ SOMO in each case, while the series of complexes $[Fe(NO)_2(SR)_2]^-$ and $[Fe(NO)(SR)_3]^-$ (R = alkyl; see Section VI,B) have (*23, 55*) $A(^{14}N)$ values clearly indicative of a π SOMO in every case.

VI. Chemical Reactivity

The reactions of the anion $[Fe_2S_2(NO)_4]^{2-}$ with electrophiles have already been described (Section II,B,2). Apart from these reactions, most of the chemistry so far reported for iron–sulfur–nitrosyl systems involves the dinuclear complexes $[Fe_2(SR)_2(NO)_4]$, the tetranuclear $[Fe_4S_3(NO)_7]^-$ and $[Fe_4S_4(NO)_4]$, and the paramagnetic mononuclear species $[Fe(NO)_2(SR)_2]^-$ and $[Fe(NO)(SR)_3]^-$, which prove to be important reactive intermediates in a wide range of reactions.

A. REDOX REACTIONS

Most of the reactions of the $[Fe_4S_3(NO)_7]^-$ salts described by Roussin in his original report (*1*) on $[Fe_4S_3(NO)_7]^-$ and $[Fe_2S_2(NO)_4]^{2-}$ were redox reactions: with a number of simple metal salts such as $AgNO_3$ or

$Hg(NO_3)_2$, oxidation of $[Fe_4S_3(NO)_7]^-$ occurred with liberation of nitrogen oxides and presumably complete breakup of the cluster; oxidants such as $KMNO_4$, PbO, HgO, and elemental halogens also liberated nitrogen oxide from $[Fe_4S_3(NO)_7]^-$. None of these investigations was other than qualitative, since Roussin had no adequate knowledge of the composition of his salt. More recently (*88*) it was reported that the reaction between $[Fe_4S_3(NO)_7]^-$ and $[Fe(CN)_6]^{3-}$ involved the transfer of three electrons per cluster, but no reaction products were characterized.

Cyclic voltammetry on $[Fe_4S_4(NO)_4]$ showed (*37*) two reversible one-electron reduction waves corresponding to reduction of the neutral complex to $[Fe_4S_4(NO)_4]^-$ and thence to $[Fe_4S_4(NO)_4]^{2-}$, rather than to oxidation to $[Fe_4S_4(NO)_4]^+$ and reduction to $[Fe_4S_4(NO)_4]^-$ as reported in a preliminary communication (*89*); chemical reduction with, for example, $[(\eta^5\text{-}C_5H_5)_2Co]$, sodium amalgam, or potassium metal in the presence of 2,2,2-crypt yields salts of $[Fe_4S_4(NO)_4]^-$ (*37*), whose structural characterization was described in Section III,C. Isolation and characterization of the dianion $[Fe_4S_4(NO)_4]^{2-}$ have not yet been reported. However, in the analogous selenium system, where cyclic voltammetry again showed (*52*) two reversible one-electron reduction waves corresponding to reduction of $[Fe_4Se_4(NO)_4]$ to $[Fe_4Se_4(NO)_4]^-$ and thence to $[Fe_4Se_4(NO)_4]^{2-}$, salts of both anions were isolated; the dianion appears to be rather labile, and only the monoanion has been characterized (*52*).

In like manner, cyclic voltammetry indicates a one-electron reduction of $[Fe_4S_2(NO)_4(NCMe_3)_2]$ (*41*), and by use of sodium amalgam as reductant the monoanion $[Fe_4S_2(NO)_4(NCMe_3)_2]^-$ was isolated as its $(Ph_3PNPPh_3)^+$ salt. The heterometallic cubanes **19** and **21** each show two reversible one-electron reduction waves in cyclic voltammetry (*26*), indicative of the formation of $[(LV)_2Fe_2(NO)_2S_4]^-$ and $[(LV)_2Fe_2(NO)_2S_4]^{2-}$ and of $[(LV)_2FeCo(NO)_2S_4]^-$ and $[(LV)_2FeCo(NO)_2S_4]^{2-}$, respectively ($L = \eta^5\text{-}MeC_5H_4$), although the isolation of these anionic products has not yet been reported.

In contrast to the stepwise reduction of $[Fe_4S_4(NO)_4]$, $[Fe_4Se_4(NO)_4]$, and the heterometallic cubanes **19** and **21**, cyclic voltammetry of the diiron complex $[Fe_2(TePh)_2(NO)_4]$ showed (*52*) a single reversible two-electron wave corresponding to reduction to $[Fe_2(TePh)_2(NO)_4]^{2-}$, salts of which were subsequently isolated by chemical reduction. This dianion is a 36-electron species, and hence is isoelectronic with the neutral cobalt complexes $[Co_2(SR)_2(NO)_4]$ (*26*); it thus lacks an Fe–Fe bond.

A further synthetically useful chemical reduction has been found in the reactions of $[Fe_4X_4(NO)_4]$ (X = S or Se) with carbon monoxide under pressure (*81*): the 60-electron clusters $[Fe_4X_4(NO)_4]$ were thereby converted to the 72-electron clusters $[Fe_4X_4(CO)_{12}]$.

In contrast, synthetically useful oxidations are so far few in number, but reaction of the 66-electron species $[Fe_4X_3(NO)_7]^-$ with elemental X (X = S or Se) provides (*27, 53*) good yields of the 60-electron cubanes $[Fe_4X_4(NO)_4]$; although excellent routes exist to $[Fe_4X_4(NO)_4]$ from $Hg[Fe(CO)_3NO]_2$ (*37, 52*), synthesis from $[Fe_4X_3(NO)_7]^-$ is probably the most convenient method when isotopically enriched cubanes are required.

B. CONVERSION OF DI- AND TETRAIRON COMPLEXES INTO PARAMAGNETIC MONOIRON COMPLEXES

1. *Diiron Complexes*

Although the neutral diiron species $[Fe_2(SR)_2(NO)_4]$ give sharp, unshifted ^1H NMR spectra in noncoordinating or weakly coordinating solvents, in solvents which are good coordinating agents such as dimethylformamide (DMF) or dimethyl sulfoxide (DMSO), only very broad, unresolved absorptions were observed in the ^1H NMR spectra (*65*) of $[Fe_2(SMe)_2(NO)_4]$. Subsequent examination (*23*) by ESR spectroscopy, of solutions of $[Fe_2(SMe)_2(NO)_4]$ in a range of coordinating solvents, gave clear evidence of the formation of paramagnetic mononuclear dinitrosyliron complexes. Two types of solvocomplex were identified: $[Fe(NO)_2(L)_2]^+$ (L = solvent), in which both RS^- groups have been displaced, and $[Fe(NO)_2(SMe)L]$, in which the RS groups remain bound to iron. The principal ESR parameters for a range of solvocomplexes formed from $[Fe_2(SMe)_2(NO)_4]$ are summarized in Table III; a similar range of solvocomplexes from $[Fe_2(SPr^i)_2(NO)_4]$ was also characterized. The case of formation of solvocomplexes was further demonstrated by the formation (*23*) of such a complex—having $g = 2.030$, but having no resolvable hyperfine coupling—simply by dissolving $[Fe_2(SCH_2COOH)_2(NO)_4]$ in water. The solvocomplexes all have g values close to 2.03, and, in general, π-acceptor solvents form complexes of the type $[Fe(NO)_2(L)_2]^+$, while solvents with little or no π-bonding capacity as ligands form neutral solvocomplexes of the type $[Fe(NO)_2(SR)(L)]$. With DMF or dimethylacetamide as solvent, both possible solvocomplexes are observed.

By use of a more strongly nucleophilic reagent RS^-, again in DMF as solvent, very ready conversion of $[Fe_2(SR)_2(NO)_4]$ to $[Fe(NO)_2(SR)_2]^-$ occurs (*23*) [Eq. (14)].

TABLE III

ESR CHARACTERISTICS OF SOLVOCOMPLEXES FORMED FROM $[Fe_2(SMe)_2(NO)_4]$

Solvent	Complex	g	$A(^{14}N)$[a]	$A(^{1}H)(SR)$[a]	$A(X)$[a]
DMF	$[Fe(NO)_2(DMF)_2]^+$	2.033	2.4(2N)	—	4.0(2H)
	$[Fe(NO)_2(SMe)(DMF)]$	2.027	2.4(2N)	4.5(3H)	4.6(1H)
DMSO	$[Fe(NO)_2(SMe)(DMSO)]$	2.032	6.0(2N)	3.2(3H)	—[b]
Pyridine (py)	$[Fe(NO)_2(py)_2]^+$	2.031	2.2(2N)	—	4.5(2N)
2,6-Dimethylpyridine	$[Fe(NO)_2(S)_2]^+$[c]	2.031	2.3(2N)	—	4.6(2N)
Quinoline	$[Fe(NO)_2(S)_2]^+$[c]	2.032	2.2(2N)	—	4.4(2N)
Et_2NH	$[Fe(NO)_2(SMe)(Et_2NH)]$	2.030	4.0(2N)	2.0(3H)	—[b]
Pyrrolidine (pyr)	$[Fe(NO)_2(SMe)(pyr)]$	2.029	3.9(2N)	2.0(3H)	—[b]
Piperidine (pip)	$[Fe(NO)_2(SMe)(pip)]$	2.029	4.2(2N)	2.1(3H)	—[b]

[a] A values in gauss; X represents ^{1}H or ^{14}N in coordinated solvent molecules.

[b] Hyperfine coupling not resolved.

[c] S represents 2,6-dimethylpyridine or quinoline.

$$[Fe_2(SR)_2(NO)_4] + 2RS^- \longrightarrow 2[Fe(NO)_2(SR)_2]^- \qquad (14)$$

Alternatively, base can be added to a solution of $Fe_2(SR)_2(NO)_4$ in RSH [Eq. (15)].

$$[Fe_2(SR)_2(NO)_4] + 2RSH \xrightarrow{\text{base}} 2[Fe(NO)_2(SR)_2]^- \qquad (15)$$

These mononuclear species give ESR spectra characterized in every case by hyperfine coupling to two ^{14}N nuclei and to the α hydrogens, when present, of the SR groups (*23, 55*) (Table IV). If base is added

TABLE IV

ESR CHARACTERISTICS OF $[Fe(NO)_2(SR)_2]^-$ AND $[Fe(NO)(SR)_3]^-$

	$[Fe(NO)_2(SR)_2]^-$			$[Fe(NO)(SR)_3]^-$	
R	g	$A(^{14}N)$ (G)	$A(^{1}H)$ (G)	g	$A(^{14}N)$ (G)
H	2.028	2.7	0.5(2H)	2.020	5.0
Me	2.028	2.1	2.1(6H)	2.021	4.5
Et	2.027	2.0	2.6(4H)	2.021	4.6
i-Pr	2.027	2.5	1.3(2H)	2.021	5.0
t-Bu	2.027	2.7	—(0H)	2.021	5.0
Ph	2.027	2.5	—(0H)	—	—
$PhCH_2$	2.028	2.4	1.4(4H)	2.021	4.8

to a dilute solution of $[Fe_2(SR)_2(NO)_4]$ in a different thiol R′SH, or if excess of $R'S^-$ is added to a DMF solution of $[Fe_2(SR)_2(NO)_4]$, the product detected by ESR is always the ligand-exchanged complex $[Fe(NO)_2(SR')_2]^-$, rather than $[Fe(NO)_2(SR)_2]^-$ [Eq. (16)].

$$[Fe_2(SR)_2(NO)_4] + 2R'SH \xrightarrow{\text{base}} [Fe(NO)_2(SR')_2]^- \qquad (16)$$

The reaction of $[Fe_2(SR)_2(NO)_4]$ with RS^- proves to be the prototype of a wide range of similar reactions of $[Fe_2(SR)_2(NO)_4]$ with other nucleophiles Y^- to yield $[Fe(NO)_2(Y)_2]^-$. Examples of Y^- so far found to yield $[Fe(NO)_2(Y)_2]^-$ include $Y^- = Br^-$ or I^- (*35*), NCO^- or NCS^- (*23*), NO_2^- (*21*), and $[MoS_4]^{2-}$, which yields the dimetallic complex **15**, $[Fe(NO)_2(S_2MoS_2)]^-$ (*55*).

In the formation of each of these complexes, the incoming nucleophile becomes bound to iron. This is in contrast to the reactions of the only other iron–nitrosyl complex whose reactivity toward nucleophiles has been extensively investigated (*19, 90*), the nitroprusside ion, $[Fe(CN)_5NO]^{2-}$. In this anion, the Fe–N–O fragment is linear, both in the solid state (*91*) and in solution (*25*), just as for $[Fe_2(SR)_2(NO)_4]$, but in all its reactions with nucleophiles X^- (X^- = OH^- (*92*), SH^- (*93*), RS^- (*94*), amines (*95, 96*), NO_2^- (*25*), N_3^- and NH_2OH (*97*), and carbanions (*98, 99*), the incoming nucleophile is bonded to the nitrogen atom of the nitrosyl ligand; [SO_3^{2-} is probably bonded to the oxygen of the nitrosyl ligand (*100–102*)]. Empirical correlations have been described (*19, 103, 104*) which indicate that metal–nitrosyl complexes having $\nu(NO) > 1880\ cm^{-1}$ undergo addition of nucleophiles to the nitrogen of the nitrosyl ligand; that complexes having $1880\ cm^{-1} > \nu(NO) > 1800\ cm^{-1}$ undergo no reactions with nucleophiles; and that complexes having $1800\ cm^{-1} > \nu(NO)$ undergo addition of nucleophiles to the metal. In $[Fe(CN)_5NO]^{2-}$, $\nu(NO)$ is $1938\ cm^{-1}$ (*19*), whereas in $[Fe_2(SR)_2(NO)_4]$, $\nu(NO)$ always falls below $1800\ cm^{-1}$ (*63*); hence the difference between $Fe_2(SR)_2(NO)_4$ and $[Fe(CN)_5NO]^{2-}$ in their reactions with nucleophiles falls neatly into the correlation between reactivity and $\nu(NO)$.

2. *Tetrairon Complexes*

It was first observed (*22*) some years ago that although aqueous solutions of $[Fe_4S_3(NO)_7]^-$ gave no ESR spectra at neutral pH, raising the pH gave the spectrum of a mononitrosyl species characterized by $g = 2.027$ and $A(^{14}N) = 4.7$ G. On the other hand, in DMF solution

$[Fe_4S_3(NO)_7]^-$ gives (*23*) a complex ESR spectrum indicative of the presence of at least three paramagnetic species. These presumably include solvocomplexes.

When $[Fe_4S_3(NO)_7]^-$ reacts with RS^- in DMF solution, then, for a range of substituents R, the products are (*23*) $[Fe(NO)_2(SR)_2]^-$, as formed from $[Fe_2(SR)_2(NO)_4]$, together with $[Fe(NO)(SR)_3]^-$; in this latter series (Table IV), although the $A(^{14}N)$ value depends upon R, no hyperfine coupling to the α-hydrogen atoms in R was resolved, so that all the spectra of $[Fe(NO)(SR)_3]^-$ comprise three lines only. The mononitrosyl complexes are fairly short lived, and within 2 days only the dinitrosyl complexes were detectable. Since the formal oxidation states of iron in $[Fe(NO)_2(SR)_2]^-$ and $[Fe(NO)(SR)_3]^-$ are Fe(−I) and Fe(I), respectively, it is likely that $[Fe(NO)_2(SR)_2]^-$ arises from the basal iron atoms in $[Fe_4S_3(NO)_7]^-$, and that $[Fe(NO)(SR)_3]^-$ arises from the apical iron [Eq. (17)].

$$\underset{3Fe(-I)+Fe(I)}{[Fe_4S_3(NO)_7]^-} + 9RS^- \longrightarrow \underset{3Fe(-I)}{3[Fe(NO)_2(SR)_2]^-} + \underset{Fe(I)}{[Fe(NO)(SR)_3]^-} + 3S^{2-} \qquad (17)$$

The conversion of $[Fe(NO)(SR)_3]^-$ into $[Fe(NO)_2(SR)_2]^-$ has been ascribed (*23*) to a disproportionation [Eq. (18)].

$$2[Fe^{I}(SR)_3NO]^- \longrightarrow [Fe^{-I}(NO)_2(SR)_2]^- + [Fe^{III}(SR)_4]^- \qquad (18)$$

Reaction of $K[Fe_4S_3(NO)_7]$ with KOH in molten Ph_2S_2 as solvent leads to the isolation in modest yield of $[Fe(NO)_2(SPh)_2]^-$; X-ray analysis of the $(Et_4N)^+$ salt confirmed the presence of the monomeric anion with linear Fe–N–O groups and an approximately tetrahedral iron center (*104a*).

Mononuclear complexes are formed (*23*) from $[Fe_4S_3(NO)_7]^-$ also by reaction with $Me_2NCS_2^-$, when $[Fe(NO)(S_2CNMe_2)_2]$ can be isolated in 88% yield based upon total iron, so that in addition to the apical Fe(NO) group, also the basal $Fe(NO)_2$ groups are incorporated into the product. In contrast, complete and rapid conversion of all the iron–nitrosyl fragments in $[Fe_4S_3(NO)_7]^-$ into $Fe(NO)_2$ groups is effected (*23*) by reaction of $Na[Fe_4S_3(NO)_7]\cdot H_2O$ with $NaNO_2$ in DMF, yielding $[Fe(NO)_2(SH)_2]^-$, but no mononitrosyl complexes. With $[MoS_4]^-$, $[Fe_4S_3(NO)_7]^-$ forms not only $[Fe(NO)_2(SH)_2]^-$ and $[Fe(NO)(SH)_3]^-$ but also $[Fe(NO)(S_2MoS_2)_2]^{2-}$ (*55*).

It appears that mononitrosyliron fragments $\{Fe(NO)\}^7$ are favored in the presence of chelating ligands such as $[Me_2NCS_2]^-$ or $[MoS_4]^{2-}$, but that dinitrosyliron fragments $\{Fe(NO)_2\}^9$ are favored by the nonchelating ligands RS^-.

The formation of mononuclear complexes from $[Fe_4S_4(NO)_4]$ is broadly similar to formation from $[Fe_4S_3(NO)_7]^-$; thus (*23*) the anions RS^- yield the mononitrosyls $[Fe(NO)(SR)_3]^-$ [Eq. (19)], which are converted into the corresponding dinitrosyls, while $Me_2NCS_2^-$ yields $[Fe(NO)(S_2CNMe_2)_2]$.

$$[Fe_4S_4(NO)_4] + 12RS^- \longrightarrow 4[Fe(NO)(SR)_3]^- + 4S^{2-} \tag{19}$$

The mononuclear dinitrosyl complexes $[Fe(NO)_2(SR)_2]^-$ are readily formed in DMF solution from both diiron and tetrairon precursors; when a DMF solution of such a complex is made less polar by addition of a large volume of benzene or toluene, the green $[Fe(NO)_2(SR)_2]^-$ is rapidly and smoothly converted to red $[Fe_2(SR)_2(NO)_4]$ [Eq. (20)].

$$2[Fe(NO)_2(SR)_2]^- \xrightarrow[\text{solvent}]{\text{nonpolar}} 2RS^- + [Fe_2(SR)_2(NO)_4] \tag{20}$$

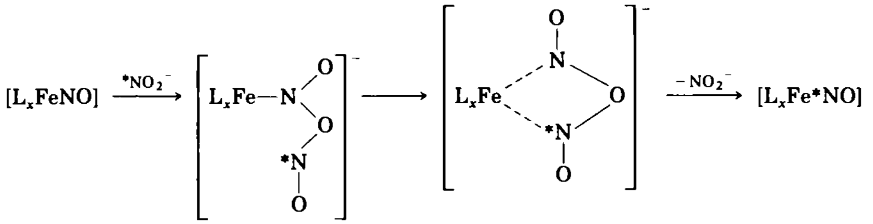
The process described in Eq. (20) is effectively the reverse of that described by Eq. (15).

C. LIGAND SUBSTITUTION REACTIONS

Mononuclear solvocomplexes of types $[Fe(NO)_2(L)_2]^+$ and $[Fe(NO)_2(SR)(L)]$ (L = solvent) are intermediates (*23*) in the thiol exchange reaction [Eq. (21)], and the proposed exchange mechanism is shown in Scheme 3. With the exception of $[Fe(NO)_2(SR)(SR')]^-$, all of the complexes in Scheme 3, and all of the individual equilibria, were observed (*23*) for at least one combination of R,R′ and solvent L. In aromatic solvents such as pyridine the exchange proceeds (*23*) solely via $[Fe(NO)_2(L)_2]^+$, in solvents such as Et_3N solely via $[Fe(NO)_2(SR)(L)]$, and in solvents such as DMF, the exchange proceeds via both routes.

$$[Fe_2(SR)_2(NO)_4] + 2R'SH \longrightarrow 2RSH + [Fe_2(SR')_2(NO)_4] \tag{21}$$

In addition to rapid exchange of thiolate ligands with R′SH and for $R'S^-$, the mononuclear complexes $[Fe(NO)_2(SR)_2]^-$ also undergo (*23*) rapid exchange of the nitrosyl ligands in the presence of isotopically labeled nitrite; a W-shaped N_2O_3 intermediate was proposed (*23*) [Eq. (22)].

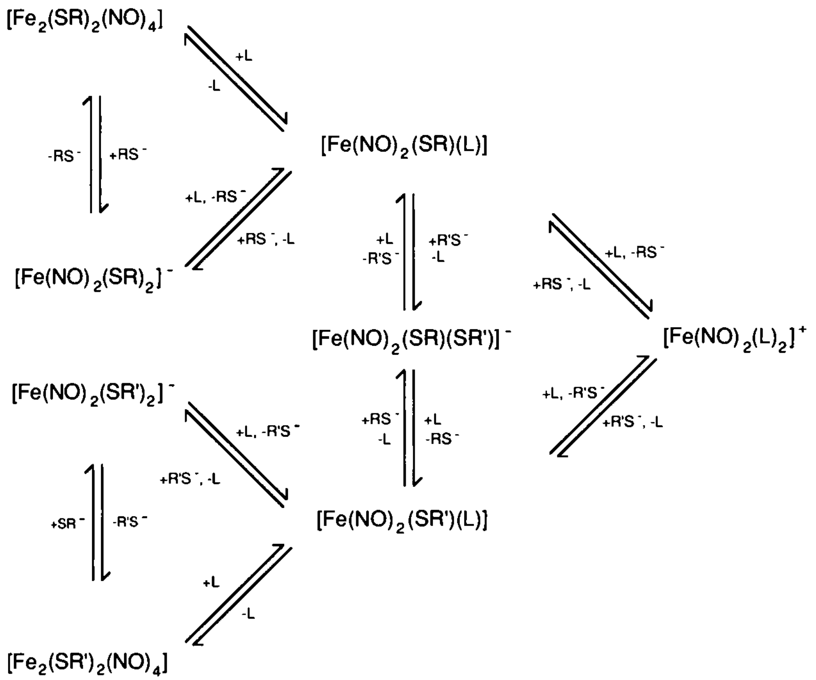


(22)

Similar fast exchange occurs with $[Fe(NO)(S_2CNMe_2)_2]$ (*23*).

The very ready interconversion of $Fe(NO)^{2+}$ and $Fe(NO)_2^+$ fragments has already been described (Section VI,B).

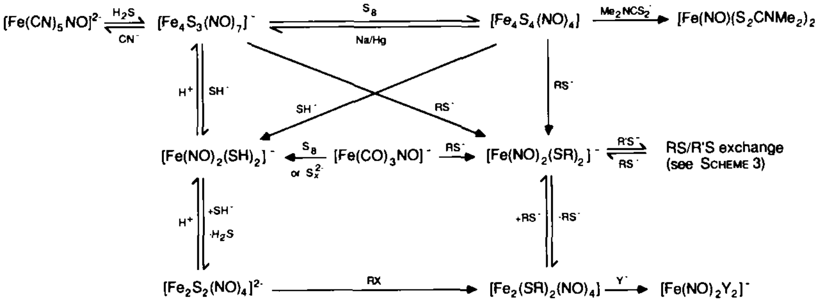
One of the most striking and surprising of the substitution reactions of $[Fe_4S_3(NO)_7]^-$ is its conversion into nitroprusside $[Fe(CN)_5NO]^{2-}$. In his original paper (*1*) describing the synthesis of $[Fe_4S_3(NO)_7]^-$ and $[Fe_2S_2(NO)_4]^{2-}$, Roussin suggested a close connection between these anions and the nitroprusside ion, even though he did not know the constitutions, or even the accurate compositions, of any of them; he claimed also to have interconverted $[Fe_4S_3(NO)_7]^-$ and



SCHEME 3. Proposed mechanisms of thiolate exchange in $[Fe_2(SR)_2(NO)_4]$. Ref. *23*.

$[Fe(CN)_5NO]^{2-}$. This surprising claim has recently been substantiated (*105*). Reaction of $[Fe_4S_3(NO)_7]^-$ with excess cyanide in aqueous solution gives $[Fe(CN)_5NO]^{2-}$, in quantitative yield based upon iron, while reaction of excess H_2S with a hot aqueous solution of $[Fe(CN)_5NO]^{2-}$ provides, after extraction, $[Fe_4S_3(NO)_7]^-$ in quantitative yield, based upon nitrosyl ligands as the limiting factor. The formation of $[Fe(CN)_5NO]^{2-}$ must necessarily involve the fragmentation of the Fe_4S_3 core of $[Fe_4S_3(NO)_7]^-$, whose formation from $[Fe(CN)_5NO]^{2-}$ must in turn involve the spontaneous self-assembly of the cluster; otherwise, no mechanistic detail is known about these remarkable transformations. The formation of $[Fe_4S_3(NO)_7]^-$ in the reaction between $[Fe(CN)_5NO]^{2-}$ and dithioacetoin $CH_3C(S)CH(SH)CH_3$ (*106*) is presumably dependent upon the formation of H_2S by hydrolysis of the dithioacetoin.

The important reactions giving rise to mononuclear intermediates and some of the important ligand substitution reactions are summarized in Scheme 4. The interconversions summarized in Schemes 3 and 4 point to the central role played by the paramagnetic mononuclear complexes $[Fe(NO)_2(SR)_2]^-$ is much of the chemistry of iron–sulfur–nitrosyl systems. Regardless of whether the initial reacting complex is mononuclear, e.g., $[Fe(CO)_3NO]^-$ or $[Fe(NO)(S_2CNMe_2)_2]$, dinuclear, e.g., $[Fe_2(SR)_2(NO)_4]$, or tetranuclear, e.g., $[Fe_4S_4(NO)_4]$ or $[Fe_4S_3(NO)_7]^-$, many reactions proceed via common intermediates. All of the substitution reactions of $[Fe_2(SR)_2(NO)_4]$, $[Fe_4S_3(NO)_7]^-$, and $[Fe_4S_4(NO)_4]$ which have so far been studied in any detail appear, with the exception of the reactions of $[Fe_2S_2(NO)_4]^{2-}$ with electrophiles, to proceed via paramagnetic mononuclear intermediates. So also do a number of synthetic routes to the



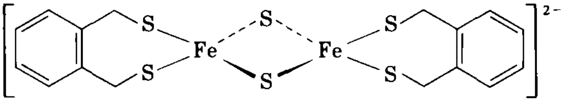
SCHEME 4. Important substitution reactions of iron–sulfur–nitrosyl systems.

diiron and tetrairon complexes, especially those from $[Fe(CO)_3NO]^-$ and $[Fe_2I_2(NO)_4]$ (*23, 35*).

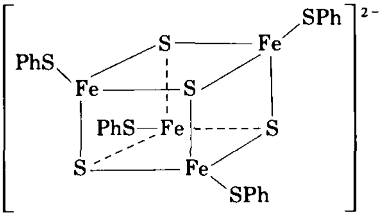
D. Nitrosylation Reactions

As well as being readily transferred from one iron center to another, in the interconversion of $Fe(NO)^{2+}$ and $Fe(NO)_2{}^+$ fragments, nitrosyl groups can also be transferred fairly readily to iron from external sources.

The preformed synthetic models (*13*) **23** and **24** for the [2Fe–2S] and [4Fe–4S] clusters, respectively, of natural redox proteins can be nitrosylated (*107*) under mild conditions with either nitric oxide or nitrite.



23



24

While nitric oxide in DMF solution yields mononuclear solvo-complexes of types $[Fe(NO)_2(SR)(L)]$ and $[Fe(NO)_2(L)_2]^+$, nitrite in aqueous solution leads via $[Fe(NO)_2(SH)_2]^-$, detected by ESR spectroscopy, to isolable $[Fe_4S_3(NO)_7]^-$ in yields of 44 and 38% from compounds **23** and **24**, respectively.

More important than the demonstration (*107*) of nitrosylation of synthetic model clusters is the demonstration (*108*) of nitrosylation by nitrite of the [4Fe–4S] center in vegetative cells of *Clostridium botulinum*. Treatment of a reduced culture of *C. botulinum* with nitrite in the presence of ascorbate resulted in loss of the ESR signal at $g = 1.94$, characteristic of the reduced iron–sulfur protein, and its replacement by a signal at $g = 2.035$, characteristic of $[Fe(NO)_2X_2]$ complexes, most likely of the $[Fe(NO)_2(SR)_2]^-$ type.

Although many of the details remain to be clarified, transfer of nitrosyl groups onto preformed iron–sulfur frameworks of the natural type is well established (*107, 108*). The transfer of nitrosyl groups from iron–sulfur–nitrosyl complexes to atoms other than iron is more problematical, as reported work on the ability of these complexes to nitrosate secondary amines RR′NH, with formation of secondary nitrosamines RR′NNO, has provided conflicting conclusions.

Initial reports (*12, 109*) indicated the ready nitrosation of a range of secondary amines by $[Fe_2(SMe)_2(NO)_4]$; however, in a more recent, thorough study on morpholine and pyrrolidine it was found (*110*) that although these underwent slow nitrosylation by $Fe_2(SMe)_2(NO)_4$ in air, under anaerobic conditions no nitrosylation occurred. However, these reactions were carried out in methylene chloride solution, and it is possible that in a coordinating solvent where solvocomplexes $[Fe(NO)_2(SMe)(L)]$ and $[Fe(NO)_2(L)_2]^+$ are present, the rate of nitrosyl transfer may be higher: this possibility awaits investigation. In buffered aqueous acetone, when solvocomplexes are probably only present in very low concentration, the pH profiles reported (*110*) for the nitrosation of morpholine and pyrrolidine by $[Fe_2(SMe)_2(NO)_4]$ show, for morpholine, an essentially constant rate over the pH range 4–11, with faster rates at extremes of pH; for pyrrolidine the rate increases steadily over the pH range 1–13. A similar *in vivo* study in rate on the nitrosation of proline by $[Fe_2(SMe)_2(NO)_4]$ showed (*110*) slow formation of *N*-nitrosoproline, at a rate much faster than the background nitrosation found in the absence of $[Fe_2(SMe)_2(NO)_4]$.

For both the *in vitro* studies with morpholine and pyrrolidine and the *in vivo* study with proline, it was observed that "partially decomposed" $[Fe_2(SMe)_2(NO)_4]$ was a much more potent nitrosation agent than the pure complex (*110*). The nature of the decomposition was not reported, and it is not clear what the significance of this report may be, although nitrite was probably present in the decomposed material.

In view of these disparate findings (*12, 109, 110*) there is a need for a systematic product and rate study of the nitrosating ability of $[Fe_2(SMe)_2(NO)_4]$ toward amines. It is likely that this will be substantially less than that of $[Fe(CN)_5NO]^{2-}$ (*95*), judged by the respective NO stretching frequencies (*19, 103, 104*).

E. ANALYTICAL APPLICATIONS

The formation by $[Fe_4S_3(NO)_7]^-$ of water-insoluble salts with protonated amines has led (*111*) to its use as a gravimetric reagent for the microdetermination of naturally occurring nitrogenous bases such as nicotinamide. The $[Fe_4S_3(NO)_7]^-$ ion has also been extensively employed as a structural probe of the active sites of certain enzymes, especially the zinc enzyme carbonic anhydrase (*112–117*).

VII. Biological Chemistry

A. CANCEROUS STATES AND $g = 2.03$ COMPLEXES

Iron-centered paramagnetic complexes formed by reactions between iron salts and nitric oxide in the presence of anionic ligands, and characterized by $g = 2.03$, were first reported over 20 years ago (*22*); similar complexes, of the general type $[Fe(NO)_2X_2]^{x+}$, have subsequently been produced by reactions of iron salts and nitric oxide in the presence of halides and pseudohalides (*118*), alcohols and alkoxides (*119*), mercaptides (*120, 121*), and mercaptopurines and mercaptopyrimidines (*122*).

Similar paramagnetic iron–nitrosyl complexes, characterized by usually anisotropic g values around 2.03, have been observed (*123–125*) in extracts of rat liver following the administration of specific chemical carcinogens, such as aminoacetylfluorene (*126*) and *N*-methyl-*N′*-nitro-*N*-nitrosoguanidine (*127*), and also in extracts from many of the organs of several species of experimental animals maintained on a normal diet supplemented only by sodium nitrite and iron(II) sulfate (*128, 129*). In each of these biological studies (*123–125, 128, 129*), the identification of the $g = 2.03$ species as being of the general type $[Fe(NO)_2X_2]^{x+}$ was far from definitive, in that in general the substituent X was not positively identified; identifications were based primarily upon comparisons with the complexes originally observed (*22*) by Phillips and his colleagues. In every case the complexes were assigned constitutions of the type $[Fe(NO)_2(SR)_2]^-$, where R was unidentified but where SR may be taken either to be cysteine or to be a peptide or protein containing cysteine at the iron-binding site.

These assignments have been placed upon a much firmer basis with the definitive characterization (*23*) of the complexes $[Fe(NO)_2(SR)_2]^-$ synthesized from $[Fe_2(SR)_2(NO)_4]$ (Section VI,B,2), and the demonstration of the formation of such $g = 2.03$ complexes from synthetic and natural $[Fe_2S_2(SR)_4]^{2-}$ and $[Fe_4S_4(SR)_4]^{2-}$ complexes under mild conditions (*107, 108*).

Thus paramagnetic monoiron complexes $[Fe(NO)_2(SR)_2]^-$ are both readily formed *in vivo* (*108, 123–125, 128, 129*) and are associated with cancerous states in experimental animals (*123–125*), although this association does not of itself imply any causal relationships.

B. The Antimicrobial Activity of $[Fe_4S_3(NO)_7]^-$ Salts

The potassium salt $K[Fe_4S_3(NO)_7]$ was many years ago shown to exhibit bacteriostatic action against a range of microorganisms, including both aerobic and anaerobic types (*130–132*); its antiseptic action was shown (*130*) to provide a good disinfectant of contaminated drinking water.

When nitrite, a well-known and widely used food preservative, is heated either with meat products or with appropriate culture media, an inhibitor is formed active against several *Clostridium* and *Salmonella* species (*133–137*); several types of iron–sulfur–nitrosyl complexes have been investigated as the possible active agents (*138–141*). The complex $[Fe_4S_3(NO)_7]^-$ was shown (*138–140*) to inhibit *Clostridium* species and to be formed (*140*) when nitrite was autoclaved with a test medium containing iron(II) sulfate and cysteine: at the same time it was shown (*140*) that neither *S*-nitrosocysteine nor $[Fe_2S_2(NO)_4]^{2-}$ could be produced under conditions which produced $[Fe_4S_3(NO)_7]^-$. The complex isolated from a culture medium of acid-hydrolyzed casein, ascorbate, and nitrite was shown (*140*) chemically and spectroscopically to have a very close resemblance to an alkali metal salt of $[Fe_4S_3(NO)_7]^-$, although identity was not proved.

While these observations indicate that $[Fe_4S_3(NO)_7]^-$ both acts as a clostridial inhibitor and can be isolated from nitrite-treated proteins, it does not follow that the intact anion is the active species. As discussed in Section VI,D, the action of nitrite upon preformed iron–sulfur clusters leads to the formation of paramagnetic mononuclear dinitrosyliron complexes (*107, 108*), while (Section VI,B) similar complexes are also readily formed (*23*) from intact $[Fe_4S_3(NO)_7]^-$, and hence complexes of the type $[Fe(NO)_2(SR)_2]^-$ are plausibly the active species in the antimicrobial action of both nitrite and $[Fe_4S_3(NO)_7]^-$. Consistent with this view, it has been found (*142*) that both $[Fe_4S_3(NO)_7]^-$ and the mononuclear complex $[Fe(NO)_2(SCH_2CHNH_2COOH)_2]^-$, derived from cysteine, were inhibitors of *Clostridium sporogenes* in culture medium; although the required dosage of the mononuclear complexes (180 μmol dm^{-1}) was higher than that of $[Fe_4S_3(NO)_7]^-$ (42 μmol dm^{-3}), these figures reflect not only the potency of the complexes but also their lability during administration.

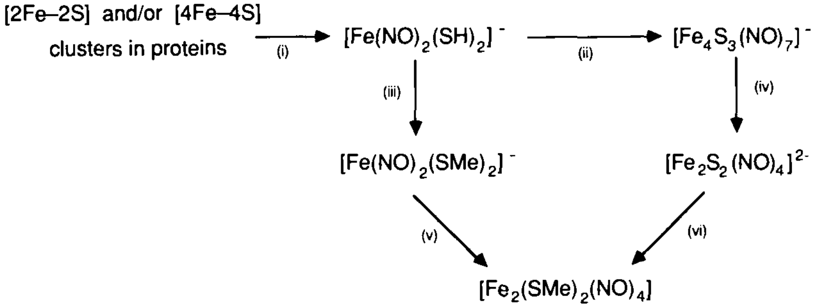
The central role of the complexes $[Fe(NO)_2(SR)_2]^-$ in the reaction chemistry of iron–sulfur–nitrosyl complexes and their very ready formation both in *in vitro* and *in vivo* (*108, 123–125, 128, 129*) suggest that the antimicrobial activity of nitrite depends not only upon the disruption of respiration [by destruction of the natural iron–sulfur clusters of redox proteins (*108*)] but also specifically upon the formation of $[Fe(NO)_2(SR)_2]^-$ species, whose exact role is, however, as yet undefined. This would provide a ready interpretation of the antimicrobial action of $[Fe_4S_3(NO)_7]^-$.

C. $[Fe_2(SMe)_2(NO)_4]$ AS A NATURAL PRODUCT

During a search for abnormal components in the diet of peasants living in Linxian, Henan Province, China (cf. Section VII,D), $[Fe_2(SMe)_2(NO)_4]$ was detected by gas chromatography/mass spectrometry (GC/MS) in vegetables which had been preserved by storage in water (*12, 143, 144*). Although $[Fe_2(SMe)_2(NO)_4]$ cannot be detected in the freshly harvested plants, during the preservation period its concentration builds up to levels in the range 0.1–0.45 mg/kg of plant matter (*145*). It is not found in similarly preserved vegetables from localities when nitrite levels in the local water supply are significantly lower than those in Linxian, nor where preservation in brine is practiced.

On the assumption that the Fe_2S_2 framework of naturally occurring $[Fe_2(SMe)_2(NO)_4]$ originated from either a [2Fe–2S] or a [4Fe–4S] cluster in a redox protein, a plausible biosynthetic route for the formation of $[Fe_2(SMe)_2(NO)_4]$ based upon known chemistry is that shown in Scheme 5.

Step (i), the formation of $[Fe(NO)_2(SH)_2]^-$ by reaction of nitrite (e.g., from groundwater or by reduction of nitrate) with preformed iron–sulfur clusters, is known to proceed readily (*107, 108*), and step (ii), the conversion of $[Fe(NO)_2(SH)_2]^-$ to $[Fe_4S_3(NO)_7]^-$ under appropriate conditions of pH, has also been demonstrated (*23*) (cf. also Scheme 4).



SCHEME 5. Possible biosynthetic pathways to $[Fe_2(SMe)_2(NO)_4]$: individual steps (i)–(vi) are discussed in the text.

Step (iv), the conversion of $[Fe_4S_3(NO)_7]^-$ to $[Fe_2S_2(NO)_4]^{2-}$, normally requires high pH if no external source of sulfur is provided (*1, 3, 20, 21*); an attractive alternative for near-neutral pH conditions is enzyme-mediated sulfur transfer, but this has not yet been investigated. Likewise, methylation of $[Fe(NO)_2(SH)_2]^-$ to provide $[Fe(NO)_2(SMe)_2]^-$, step (iii), has not been investigated yet.

Step (v), conversion of $[Fe(NO)_2(SMe)_2]^-$ to the product $[Fe_2(SMe)_2(NO)_4]$, occurs spontaneously under the appropriate conditions of solvent polarity/polarizability (*23*) [cf. Eq. (20) and Schemes 3 and 4]. Step (vi) requires the methylation of $[Fe_2S_2(NO)_4]^{2-}$; while this has been demonstrated for methylation by methyl halides (*3, 24, 29*), methylation by biological methyl transfer, e.g., from methionine or *S*-adenosylmethionine, has yet to be investigated. Thus, although neither of the biosynthetic routes suggested in Scheme 5 has yet been fully investigated, several of the steps [(i), (ii), and (vi)], are established, while others [(iv) and (vi)] are already known to occur under nonbiological conditions.

D. $[Fe_2(SMe)_2(NO)_4]$ (Roussin Esters) and Chemical Carcinogenesis

The results of a major epidemiological study of the geographical variations in the occurrence throughout China of a wide variety of different types of cancer have recently been published in the form of an atlas (*146*). One result of this survey was the revelation of a very high, but very localized, incidence of esophageal cancer in the Linxian valley of Henan province in northern China (*146, 147*). Esophageal cancer also exhibits very high incidence in a number of other localities in both Asia and Africa (*148*), but the Chinese occurrence has so far attracted the most international attention.

In Linxian, where the adult incidence of esophageal cancer can be as high as one in four, the condition develops through mild and severe stages of epithelial hyperplasia, although reversible changes or recurring processes are frequently encountered (*149*).

The probable role of local foodstuffs in the development of esophageal cancer in Linxian was deduced from a study of domestic poultry. Poultry reared in Linxian commonly suffer from cancer of the gullet, analogous to human esophageal cancer. When part of the Linxian human population was rehoused some distance away and was provided with poultry free of gullet cancer, feeding of these birds with food scraps prepared by methods normal in Linxian caused rapid development of gullet cancers.

Among the dietary staples in the rural communities of the Linxian valley are millet, cornbread, and the pickled vegetables previously mentioned (Section VII,C), prepared by storing fresh green leaves in water over several weeks. The water supply is rather high in both nitrate and nitrite.

When consumed, the cornbread is often contaminated with the mold *Fusarium moniliforme*, and it has been shown (*150, 151*) that this mold, in the presence of nitrite, will elaborate a range of *N*-nitroso compounds: Me_2NNO, Et_2NNO, $Me(PhCH_2)NNO$, and $(Me_2CHCH_2CH_2)(CH_3COCHMe)NNO$. Cornbread contaminated in this way induces tumors in rats (*150*).

Just as the cornbread is often contaminated with *F. moniliforme*, so too the preserved vegetables are generally contaminated with *Geotrichum candidum*. The formation of these molds is not necessarily indicative of poor domestic hygiene, rather they are regarded by some as an enhancement (cf. certain Western European cheeses). Extracts of these preserved vegetables were found (*152*) to induce stomach cancers in mice and rats, and $[Fe_2(SMe)_2(NO)_4]$ could be isolated from vegetables preserved in this way (*12, 143–145, 152*).

The complex $[Fe_2(SMe)_2(NO)_4]$ has been found to have only weak mutagenic properties when employed alone (*149, 152–154*), although it potentiated the action of 3-methylcolanthrene (*154*). A recent study of the effects of $[Fe_2(SMe)_2(NO)_4]$ and $Me(PhCH_2)NNO$ upon mice found (*155*) that while $[Fe_2(SMe)_2(NO)_4]$ alone caused no lesions in the esophagus or the forestomach, it markedly enhanced the lesion count induced by $Me(PhCH_2)NNO$; thus it promotes the tumorigenic properties of $Me(PhCH_2)NNO$.

Hence although $[Fe_2(SMe)_2(NO)_4]$ is formed in the preservation of vegetables, presumably under the action of *G. candidum*, only when these are consumed along with moldy cornbread (or some other source of nitrosamines) is the complex likely to prove harmful. The action of the mold in the formation of $[Fe_2(SMe)_2(NO)_4]$ has not been fully established. It is perhaps significant that in urban Beijing, vegetables preserved in the same way contained no more that 5×10^{-3} mg kg^{-1} of $[Fe_2(SMe)_2(NO)_4]$ (*144*), and the incidence of esophageal cancer is low.

A further dietary component which may potentiate the carcinogenic action of *N*-nitrosamines is millet, which contains silica fibers (*156*), known to promote the carcinogenic action of 11-methyl-15-cyclopenta[*a*]phenanthrene (*157*), and presumably of certain other carcinogens also.

Thus, although the weak mutagenicity of $[Fe_2(SMe)_2(NO)_4]$ is hardly consistent with its being the sole cause of esophageal cancer in Linxian, its presence in food there (and, as far as is known, nowhere else), and the very high incidence of just one kind of cancer in Linxian, strongly suggest some connection between the two. Possibly the lipid solubility of $[Fe_2(SMe)_2(NO)_4]$ and its nitrosating activity give it a unique *in vivo* activity. Compounds of this type are a challenge not only to our understanding of iron–sulfur cluster chemistry, but also to a full appreciation of chemical carcinogenesis.

REFERENCES

1. Roussin, F. Z., *Ann. Chim. Phys.* **52,** 285 (1858).
2. Playfair, L., *Ann. Chem. Pharm.* **74,** 340 (1850).
3. Pavel, O., *Ber. Dtsch. Chem. Ges.* **15,** 2600 (1882).
4. Hofmann, K. A., and Wiede, O. F., *Z. Anorg. Allgem. Chem.* **9,** 295 (1895).
5. Reihlen H., and von Friedolsheim, A., *Liebigs Ann. Chem.* **457,** 71 (1927).
6. Cambi, L., and Szegö, L., *Atti Accad. Lincei* **13,** 168 (1931).
7. Manchot, W., and Linckh, E., *Ber. Dtsch. Chem. Ges.* **59,** 412 (1926).
8. Seel, F., *Z. Anorg. Allgem. Chem.* **249,** 308 (1942).
9. Addison, C. C., and Lewis, J., *Q. Rev. Chem. Soc.* **9,** 115 (1955).
10. Thomas, J. T., Robertson, J. H., and Cox, E. G., *Acta Crystallogr.* **11,** 599 (1958).
11. Johansson, G., and Lipscomb, W. N., *Acta Crystallogr.* **11,** 594 (1958).
12. Wang, G. H., Zhang, W. X., and Chai, W. G., *Acta Chim. Sin.* **38,** 95 (1980).
13. Holm, R. H., *Chem. Soc. Rev.* **10,** 455 (1981).
14. Spiro, T. G., ed., "Iron-Sulphur Proteins." Wiley (Interscience), New York, 1982.
15. Garner, C. D., *In* "Transition Metal Clusters" (B. F. G. Johnson, ed.), p. 265. Wiley (Interscience), New York, 1980.
16. Johnson, B. F. G., and McCleverty, J. A., *Prog. Inorg. Chem.* **7,** 277 (1966).
17. Connelly, N. G., *Inorg. Chim. Acta Rev.* **6,** 48 (1972).
18. Enemark, J. H., and Feltham, R. D., *Coord. Chem. Rev.* **13,** 339 (1974).
19. McCleverty, J. A., *Chem. Rev.* **79,** 53 (1979).
20. Brauer, G. (ed.), "Handbuch der Präparativen Anorganischen Chemie," 2nd Ed., Vol. 2, p. 1526. Enke, Stuttgart, 1960.
21. Butler, A. R., Glidewell, C., and Johnson, I. L., unpublished work.
22. McDonald, C. C., Phillips, W. D., and Mower, H. F., *J. Am. Chem. Soc.* **87,** 3319 (1965).
23. Butler, A. R., Glidewell, C., Hyde, A. R., and Walton, J. C., *Polyhedron* **4,** 797 (1985).
24. Beck, W., Grenz, R., Götzfried, F., and Vilsmaier, E., *Chem. Ber.* **114,** 3184 (1981).
25. Butler, A. R., Glidewell, C., Hyde, A. R., and McGinnis, J., *Inorg. Chem.* **24,** 2931 (1985).
26. Weatherill, T. D., Ph.D. thesis, University of Illinois at Urbana-Champaign (1985).
27. Butler, A. R., Glidewell, C., Hyde, A. R., McGinnis, J., and Seymour, J. E., *Polyhedron* **2,** 1045 (1983).
28. Hieber, W., and Beck, W., *Z. Anorg. Allg. Chem.* **305,** 274 (1960).
29. Seyferth, D., Gallagher, M. K., and Cowie, M., *Organometallics* **5,** 539 (1986).
30. Rauchfuss, T. B., and Weatherill, T. D., *Inorg. Chem.* **21,** 827 (1982).
31. Mak, T. C. W., Book, L., Chung Chieh, Gallagher, M. K., Li-cheng Song, and Seyferth, D., *Inorg. Chim. Acta* **73,** 159 (1983).

32. Mazany, A. M., Fackler, J. P., Jr., Gallagher, M. K., and Seyferth, D., *Inorg. Chem.* **22,** 2593 (1983).

33. King, R. B., *J. Am. Chem. Soc.* **84,** 2460 (1962).

34. De Beer, J. A., and Haines, R. J., *J. Organomet. Chem.* **24,** 757 (1970).

35. Butler, A. R., Glidewell, C., Hyde, A. R., and Walton, J. C., *Polyhedron* **4,** 303 (1985).

36. Gall, R. S., Chu, C. T.-W., and Dahl, L. F., *J. Am. Chem. Soc.* **96,** 4019 (1974).

37. Chu, C. T.-W., Lo, F. Y.-K., and Dahl, L. F., *J. Am. Chem. Soc.* **104,** 3409 (1982).

38. Eaton, P. E., and Cole, T. W., *J. Am. Chem. Soc.* **86,** 3157 (1964).

39. Chu, C. T.-W., and Dahl, L. F., *Inorg. Chem.* **16,** 3245 (1977).

40. Gall, R. S., Connelly, N. G., and Dahl, L. F., *J. Am. Chem. Soc.* **96,** 4017 (1974).

41. Chu, C. T.-W., Gall, R. S., and Dahl, L. F., *J. Am. Chem. Soc.* **104,** 737 (1982).

42. Dymicky, M., *Proc. Schevchenko Sci. Soc. Sect. Chem. Biol. Med.* **8,** 70 (1980).

43. Butler, A. R., Glidewell, C., Hyde, A. R., and McGinnis, J., *Polyhedron* **2,** 1399 (1983).

44. Manchot, W., *Ber. Dtsch. Chem. Ges.* **59,** 2445 (1926).

45. Brauer, G., Ref. 20, p. 1528.

46. Büttner, H., and Feltham, R. D., *Inorg. Chem.* **11,** 971 (1972).

47. Ileperuma, O. A., and Feltham, R. D., *J. Am. Chem. Soc.* **98,** 6039 (1976).

48. Lalor, F. J., Brookes, L. H., Ferguson, G., and Parvez, M., *J. Chem. Soc. Dalton Trans.* 245 (1984).

49. Karlin, K. D., Rabinowitz, H. N., Lewis, D. L., and Lippard, S. J., *Inorg. Chem.* **16,** 3262 (1977).

50. McCleverty, J. A., Atherton, N. M., Locke, J., Wharton, E. J., and Winscom, C. J., *J. Am. Chem. Soc.* **89,** 6082 (1967).

51. Baltusis, L. M., Karlin, K. D., Rabinowitz, H. N., Dewan, J. C., and Lippard, S. J., *Inorg. Chem.* **19,** 2627 (1980).

52. Nelson, L. L., Ph.D. thesis, University of Wisconsin, Madison, (1981).

53. Butler, A. R., Glidewell, C., Hyde, A. R., and McGinnis, J., *Polyhedron* **3,** 1165 (1984).

54. Coucouvanis, D., Simhon, E. D., Stremple, P., and Baenziger, N. C., *Inorg. Chem. Acta* **53,** L135 (1981).

55. Butler, A. R., Glidewell, C., Johnson, I. L., and Walton, J. C., unpublished work.

56. Rauchfuss, T. B., Weatherill, T. D., Wilson, S. R., and Zebrowski, J. P., *J. Am. Chem. Soc.* **105,** 6508 (1983).

57. Bolinger, C. M., Weatherill, T. D., Rauchfuss, T. B., Rheingold, A. L., Day, C. S., and Wilson, S. R., *Inorg. Chem.* **25,** 634 (1956).

58. Brunner, H., Kauermann, H., and Wachter, J., *Angew, Chem. Int. Ed. Engl.* **22,** 549 (1983).

59. Lin Xianti., Zheng An, Lin Shanhao, Huang Jinling, and Lu Jiaxi, *J. Struct. Chem. (Wuhan)* **1,** 79 (1982).

60. Davies G. R., Jarvis, J. A. J., Kilbourn, B. K., Mais, R. H. B., and Owston, P. G., *J. Chem. Soc. (A)* 1275 (1970).

61. Colapietro, M., Domenicano, A., Scaramuzza, L., Vaciago, A., and Zambonelli, L., *J. Chem. Soc. Chem. Commun.* 583 (1967).

62. Ileperuma, O. A., and Feltham, R. D., *Inorg. Chem.* **16,** 1876 (1977).

63. Glidewell, C, and Johnson, I. L., unpublished work.

64. Butler, A. R., Glidewell, C., and Johnson, I. L., *Polyhedron* **6,** 1147 (1987).

65. Glidewell, C., and Hyde, A. R., *Polyhedron* **4,** 1155 (1985).

66. Abboud, J.-L. M., Taft, R. W., and Kamlet, M. J., *J. Chem. Res(S)* 98 (1984).

67. Kamlet, M. J., and Taft, R. W., *Acta. Chem. Scand.* **B39,** 611 (1985).

68. Bell, L. K., Mingos, D. M. P., Tew D. G., Larkworthy, L. F., Sandell, B., Povey, D. C., and Mason, J., *J. Chem. Soc. Chem. Commun.* 125 (1983).

69. Bell, L. K., Mason, J., Mingos, D. M. P., and Tew, D. G., *Inorg. Chem.* **22,** 3497 (1983).

70. Evans, D. H., Mingos, D. M. P., Mason, J., and Richards, A., *J. Organomet. Chem.* **249,** 293 (1983).

71. Wang, Y., *Huaxue Tongbao* **6,** 18 (1983); *Chem. Abstr.* **99,** 203021 (1983).

72. Sedney, D., and Reiff, W. M., *Inorg. Chim. Acta* **34,** 231 (1979).

73. Kerler, W., Nenwirth, W., Fluck, E. Kuhn, P., and Zimmerman, B., *Z. Phys.* **173,** 321 (1963).

74. Kostiner, E., Steger, J., and Rea, J. R., *Inorg. Chem.* **9,** 1939 (1970).

75. Sung, S.-S., Glidewell, C., Butler, A. R., and Hoffmann, R., *Inorg. Chem.* **24,** 3856 (1985).

76. Wade, K., *Adv. Inorg. Chem. Radiochem.* **18,** 1 (1976).

77. Mingos, D. M. P., *J. Chem. Soc. Chem. Commun.* 706 (1983).

78. Averill, B. A., Herskovitz, T., Holm, R. H., and Ibers, J. A., *J. Am. Chem. Soc.* **95,** 3523 (1973).

79. Que, L., Bobrik, M. A., Ibers, J. A., and Holm, R. H., *J. Am. Chem. Soc.* **96,** 4168 (1974).

80. Wei, C. H., Wilkes, G. R., Treichel, P. M., and Dahl, L. F., *Inorg. Chem.* **5,** 900 (1966).

81. Nelson, L. L., Lo, F. Y.-K., Rae, A. D., and Dahl, L. F., *J. Organomet. Chem.* **225,** 309 (1982).

82. Berg, J. M., Hodgson, K. O., and Holm, R. H., *J. Am. Chem. Soc.* **101,** 4586 (1979).

83. Laskowski, E. J., Reynolds, J. G., Frankel, R. B., Foner, S., Papaefthymiou, G. C., and Holm, R. H., *J. Am. Chem. Soc.* **101,** 6562 (1979).

84. Trinh-Toan, Fehlhammer, W. P., and Dahl, L. F., *J. Am. Chem. Soc.* **99,** 402 (1977).

85. Trinh-Toan, Teo, B. K., Ferguson, J. A., Meyer, T. J., and Dahl, L. F., *J. Am. Chem. Soc.* **99,** 408 (1977).

86. Bottomley, F., and Grein, F., *Inorg. Chem.* **21,** 4170 (1982).

87. Glidewell, C., and Johnson, I. L., *Inorg. Chim. Acta* **132,** 145 (1987).

88. Treadwell, W. D., and Huber, D., *Helv. Chim. Acta* **26,** 18 (1943).

89. Gall, R. S., Chu, C. T.-W., and Dahl, L. F., *J. Am. Chem. Soc.* **96,** 4019 (1974).

90. Swinehart, J. H., *Coord. Chem. Rev.* **2,** 385 (1967).

91. Manoharan, P. T., and Hamilton, W. C., *Inorg. Chem.* **2,** 1043 (1963).

92. Swinehart, J. H., and Rock, P. A., *Inorg. Chem.* **5,** 573 (1966).

93. Rock, P. A., and Swinehart, J. H., *Inorg. Chem.* **5,** 1078 (1966).

94. Morando, P. J., Borghi, E. B., de Schteingart, L. M., and Blesa, M. A., *J. Chem. Soc. Dalton Trans.* 435 (1981).

95. Maltz, H., Grant, M. A., and Navaroli, M. C., *J. Org. Chem.* **36,** 363 (1971).

96. Butler, A. R., Glidewell, C., Reglinski, J., and Waddon, A., *J. Chem. Res.* (*S*) 279, (*M*) 2768 (1984).

97. Wolfe, S. K., Andrade, C., and Swinehart, J. H., *Inorg. Chem.* **13,** 2567 (1974).

98. Wolfe, S. K., and Swinehart, J. H., *Inorg. Chem.* **7,** 1855 (1968).

99. Butler, A. R., Glidewell, C., Chaipanich, V., and McGinnis, J., *J. Chem. Soc. Perkin Trans.* **2,** 7 (1986).

100. Moser, W., Chalmers, R. A., and Fogg, A. G., *J. Inorg. Nucl. Chem.* **27,** 831 (1965).

101. Fogg, A., Norbury, A. H., and Moser, W., *J. Inorg. Nucl. Chem.* **28,** 2753 (1966).

102. Andrade, C., and Swinehart, J. H., *Inorg. Chem.* **11,** 648 (1972).

103. Bottomley, F., Brooks, W. V. F., Clarkson, S. G., and Tong, S. B., *J. Chem. Soc. Chem. Commun.* 919 (1973).

104. Bottomley, F., *Acc. Chem. Res.* **11,** 158 (1978).

104a. Strasdeit, H., Krebs, B., and Henkel, G., *Z. Naturforsch.* **41b,** 1357 (1986).

105. Glidewell, C., and McGinnis, J., *Inorg. Chim. Acta* **64,** L171 (1982).

106. Wharton, E. J., and McCleverty, J. A., *Inorg. Nucl. Chem. Lett.* **6,** 549 (1970).

107. Butler, A. R., Glidewell, C., Hyde, A. R., and Walton, J. C., *Inorg. Chim. Acta* **106,** L7 (1985).
108. Reddy, D., Lancaster, J. R., Jr., and Cornforth, D. P., *Science* **221,** 769 (1983).
109. Wang, M. Y., Li, M. H., Jiang, Y. Z., Sun, Y. H., Li, G. Y., Zhang, W. X., Chai, W. G., and Wang, G. H., *Cancer Res. Prevent. Treat.* **10,** 145 (1983).
110. Croisy, A., Ohshima, H., and Bartsch, H., *I.A.R.C. Sci. Publ.* **57,** 327 (1984).
111. Dobry, A., *Trav. Membres Soc. Chim. Biol.* **23,** 1438 (1941).
112. Dobry-Duclaux, A., *Biochim. Biophys. Acta* **39,** 33 (1960).
113. Dobry-Duclaux, A., *Makromol. Chem.* **44,** 155 (1961).
114. Dobry-Duclaux, A., *Biochim. Biophys. Acta* **54,** 76 (1961).
115. Dobry-Duclaux, A., *Biochim. Biophys. Acta* **77,** 1 (1963).
116. Dobry-Duclaux, A., *Biochim. Biophys. Acta* **89,** 1 (1964).
117. Dobry-Duclaux, A., *Bull. Soc. Chim. Biol.* **48,** 887 (1966).
118. Burlamacchi, L., Martini, G., and Tiezzi, E., *Inorg. Chem.* **8,** 2021 (1969).
119. Martini, G., and Tiezzi, E., *Trans. Faraday Soc.* **67,** 2538 (1971).
120. Jezowska-Trzebiatowska, B., and Jezierski, A., *J. Mol. Struct.* **19,** 635 (1973).
121. Boyer, M. P., Morton, J. R., and Preston, K. F., *J. Phys. Chem.* **84,** 2989 (1980).
122. Basoni, R., Gaggelli, E., Tiezzi, E., and Valensin, G., *J. Chem. Soc. Perkin Trans.* **2,** 423 (1975).
123. Woolum, J. C., and Commoner, B., *Biochim. Biophys. Acta* **201,** 131 (1970).
124. Chiang, R. W., Woolum, J. C., and Commoner, B., *Biochim. Biophys. Acta* **257,** 452 (1972).
125. Nagata, C., Ioki, Y., Kodama, M., Tagashira, Y., and Nakadate, M., *Ann. N.Y. Acad. Sci.* **222,** 1031 (1973).
126. Commoner, B., Woolum, J. C., Senturia, L. H., and Ternberg, J. L., *Cancer Res.* **30,** 2091 (1970).
127. Lawley, P. D., *Nature (London)* **218,** 580 (1968).
128. Vanin, A. F., and Varich, V. Ya., *Stud. Biophys.* **86,** 177 (1981).
129. Varich, V. Ya., and Vanin, A. F., *Biophysics* **28,** 1125 (1983).
130. Dobry, A., and Boyer, F., *Ann. Inst. Pasteur* **71,** 455 (1945).
131. Candeli, A., and Mancini, M., *Boll. Soc. Med. Chir. Modena* **48,** 3 (1948).
132. Candeli, A., *Boll. Soc. Ital. Biol. Sper.* **25,** 495 (1949).
133. Perigo, J. A., Whiting, E., and Bushford, T. E., *J. Food Technol.* **2,** 377 (1967).
134. Perigo, J. A., and Roberts, T. A., *J. Food Technol.* **3,** 91 (1968).
135. Johnston, M. A., Pivnich, H., and Samson, J. M., *Can. Inst. Food Sci. Technol. J.* **2,** 52 (1969).
136. Roberts, T. A., and Garcia, C. E., *J. Food Technol.* **8,** 463 (1973).
137. Pivnich, H., and Chang, P. C., *Proc. Int. Symp. Nitrite Meat Prod.* 111 (1973).
138. Van Roon, P. S., *Proc. Int. Symp. Nitrite Meat Prod.* 117 (1973).
139. Mirna, A., and Coretti, K., *Fleischwirtschaft* **54,** 507 (1974).
140. Ashworth, J., Didcock, A., Hargreaves, L. L., Jarvis, B., Walters, C. L., and Larkworthy, L. F., *J. Gen. Microbiol.* **84,** 403 (1974).
141. Moran, D. M., Tannenbaum, S. R., and Archer, M. C., *Appl. Microbiol.* **30,** 838 (1975).
142. Van Roon, P. S., *Proc. Eur. Meet. Meat Res. Work., 26th* **2,** 227 (1980).
143. Wang, G. H., Zhang, W. X., and Chai, W. G., *Adv. Mass Spectrom.* **8B,** 1369 (1980).
144. Zhang, W. X., Xu, M. S., Wang, G. H., and Wang, M. Y., *Cancer Res.* **43,** 339 (1983).
145. Wang, M. Y., Lu, S. H., Ji, C., Wang, Y. L., and Li, M. H., *Cancer Res. Prevent. Treat.* **10,** 12 (1983).
146. "Atlas of Cancer Maps of the People's Republic of China." China Map Press, Beijing, 1980.

147. Yang, C. S., *Cancer Res.* **40,** 2633 (1980).

148. Cook-Mozaffari, P. J., *Nutr. Cancer* **1,** 5 (1979).

149. Li, M. H., and Cheng, S. J., *Chin. Med. J.* **97,** 311 (1984).

150. Li, M. H., *Proc. Conf. Cancer Res. People's Rep. China, 1st* 131 (1980); *Chem. Abstr.* **94,** 186612v (1981).

151. Li, M. H., Lu, S. H., Ji, C., Wang, M., Wang, Y., Cheng, S., and Tiam, G., *In* "Genetic and Environmental Factors in Experimental and Human Cancer", (H. V. Galboln, ed.). Japan Science Society Press, Tokyo, 1980.

152. Li, M. H., Lu, S. H., Ji, C., Wang, Y., Wang, M., Cheng, S., and Tiam, G., *Proc. Int. Symp. Princess Takamatsu Cancer Res. Fund* 139 (1979); *Chem. Abstr.* **97,** 180397 (1982).

153. Lu, S. H., Camus, A. M., Tomatis, L., and Bartsch, H., *J. Natl. Cancer Inst.* **66,** 33 (1981).

154. Cheng, S. J., Sala, M., Li, M. H., Courtois, I., and Chouroulinkov, I., *Carcinogenesis* **2,** 313 (1981).

155. Lu, S., Lin, P., Lu, F., Wang, Y., and Wang, M., *Zhonghua Zhongliu Zazhi* **7,** 241 (1985); *Chem. Abstr.* **104,** 63958e (1986).

156. O'Neill, C., Jordon, P., Bhatt, T., and Newman, R., *Ciba Found. Symp.* **121,** 214 (1986).

157. Bhatt, T., Coombs, M., and O'Neill, C., *Int. J. Cancer* **34,** 519 (1984).