CO homologation. Soluble, strongly reducing, low-valent, transition-metal complexes are available, but with CO they form carbonyl complexes.[25] Hence, the low affinity of lanthanide ions to form stable CO complexes, the high oxophilicity of the lanthanides, and the strongly reducing Sm(II) → Sm(III) couple in soluble complexes allow distinctive CO chemistry to occur with organosamarium reagents. Further studies on these and related systems are in progress.

(25) Titanocene chemistry provides one example: Bercaw, J. E.; Marvich, R. H.; Bell, L. G.; Brintzinger, H. H. *J. Am. Chem. Soc.* **1972**, *94*, 1219–1238. Bottrill, M.; Gavens, P. D.; McMeeking, J. In "Comprehensive Organometallic Chemistry"; Wilkinson, G. W., Stone, F. G. A., Abel, E. W., Eds., Pergamon Press: Oxford, 1982; Chapter 22.2.

Carboxylate Bridge Exchange Reactions in the {Fe₂O(O₂CR)₂}²⁺ Core. Synthesis, Structure, and Properties of Phosphodiester-Bridged Complexes

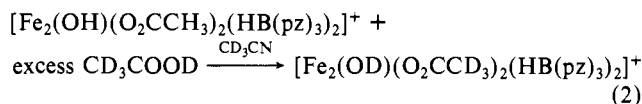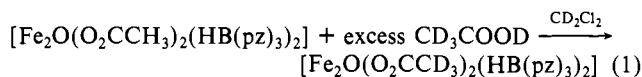William H. Armstrong and Stephen J. Lippard*

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The recently reported binuclear iron(III) complexes containing the {Fe₂O(O₂CR)₂}²⁺ core[1,2] are currently the best available structural and spectroscopic models for the spin-coupled diiron(III) centers in hemerythrin[3] and ribonucleotide reductase.[4] Reactivity studies of this core structure have been initiated.[1b,5,6] In the hydrotris(1-pyrazolyl)borate derivative, [(HB(pz)₃)FeO-(O₂CCH₃)₂Fe(HB(pz)₃)] (1), facile ¹⁸O-exchange[1b] and protonation[5] reactions of the bridging oxygen atom have been observed. The fact that protonation of the oxo bridge is accompanied by expansion of the core suggested to us that concomitant exchange reactions of the bridging carboxylate groups might be feasible. Here we describe the results of initial investigations of carboxylate bridge exchange reactions with carboxylic and diesterified phosphoric acids. Interaction of the μ-oxodiiron(III) center with phosphate esters is of interest since iron(III) phosphate interactions occur in ferritin,[7] phosvitin,[8] and Fe^{III}–ATP model complexes[9] and are possibly involved in the phosphate-containing form of uteroferrin[10] and the binding of nucleoside diphosphate substrates
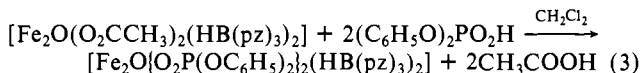
to ribonucleotide reductase. Moreover, we are concerned with the iron-promoted hydrolysis of phosphate esters[11] which may be of relevance to the phosphatase activity displayed by the purple acid phosphatases and uteroferrin.[10]

In both 1[1] and its protonated derivative, [(HB(pz)₃)Fe-(OH)(O₂CCH₃)₂Fe(HB(pz)₃)](ClO₄) (2),[5] the bridging acetate groups exchange readily with perdeuterioacetic acid in solution as revealed by proton NMR spectroscopy (Figure 1). These reactions (eq 1 and 2) were carried out at room temperature with addition of 10 and 12.5 equiv of CD₃COOD for 1 and 2, respectively. ¹H NMR spectra of the reactions, recorded ~0.5

$$[Fe_2O(O_2CCH_3)_2(HB(pz)_3)_2] + excess\ CD_3COOD \xrightarrow{CD_2Cl_2}$$
$$[Fe_2O(O_2CCD_3)_2(HB(pz)_3)_2]\quad (1)$$

$$[Fe_2(OH)(O_2CCH_3)_2(HB(pz)_3)_2]^+ +$$
$$excess\ CD_3COOD \xrightarrow{CD_3CN} [Fe_2(OD)(O_2CCD_3)_2(HB(pz)_3)_2]^+ \quad (2)$$

h after mixing, reveal that the bridged diiron(III) structures remain intact and that resonances associated with C*H*₃ of the coordinated acetate groups vanish as the perdeuterioacetate analogues are formed.

By making use of a related reaction (eq 3) we have prepared the diphenylphosphate-bridged complex, [Fe₂O{O₂P(OC₆H₅)₂}₂-(HB(pz)₃)₂] (3). To a solution of 1.002 g (1.491 mmol) of 1 in

$$[Fe_2O(O_2CCH_3)_2(HB(pz)_3)_2] + 2(C_6H_5O)_2PO_2H \xrightarrow{CH_2Cl_2}$$
$$[Fe_2O\{O_2P(OC_6H_5)_2\}_2(HB(pz)_3)_2] + 2CH_3COOH \quad (3)$$

500 mL of CH₂Cl₂ was added a solution of 0.742 g (2.98 mmol) of (C₆H₅O)₂PO₂H in 50 mL of CH₂Cl₂ dropwise over approximately 5 min. The brown-green color of 1 in solution quickly changed to emerald-green. The reaction mixture was stirred for 1 h and then the solvent was stripped off with a rotary evaporator to yield a dark green oil. This oil was dissolved in 30 mL of CCl₄, and the resulting solution was allowed to stand for 3 days at ambient temperature during which time a microcrystalline green precipitate formed. The solid was filtered, washed with 10 mL of CCl₄ and then 2 × 10 mL portions of hexanes, powdered, and dried under vacuum to afford 1.394 g (75.6%) of the CCl₄ solvate of 3. A similar procedure was used to prepare [Fe₂O{O₂P-(OC₂H₅)₂}₂(HB(pz)₃)₂]. Further purification of 3 was achieved by recrystallization from CHCl₃ with hexanes layered on top. Crystals of 3·CHCl₃ suitable for X-ray diffraction studies[12] and elemental analysis[13] were obtained by this method.

The structure of 3 (Figure 2) reveals that the oxo-bridged diiron(III) core is retained upon exchange of carboxylate for diphenylphosphate ligands. Two bidentate diphenylphosphate bridges now span the μ-oxodiiron(III) core, and the resulting {Fe₂O[O₂P(OPh)₂]₂}²⁺ unit is capped by hydrotris(1-pyrazolyl)-borate ligands. The Fe–O$_{oxo}$ distances are slightly longer in 3 than in 1, 1.808 (4) vs. 1.784 (4) Å, respectively. The larger Fe–O–Fe angles, 134.7 (3)° vs. 123.6 (1)°, and resulting greater Fe···Fe separation, 3.337 (1) vs. 3.146 (1) Å, in 3 are presumably due to the increased O···O separation in phosphate compared to carboxylate ligands. The Fe–N and Fe–O$_{phosphate}$ bond distances are typical for high-spin iron(III), and lengthening of Fe–N distances trans to the bridging oxo atoms for 3 is a feature also

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(12) X-ray analysis: The compound [Fe₂O{O₂P(OC₆H₅)₂}₂(HB(pz)₃)₂]·CHCl₃ crystallizes in the monoclinic system, space group *P*2₁/*n*, with *a* = 11.940 (2) Å, *b* = 20.105 (4) Å, *c* = 22.155 (3) Å, β = 96.56 (1)°, *V* = 5283.6 Å³, ρ_{obsd} = 1.48 (1) g cm⁻³, ρ_{calcd} = 1.473 g cm⁻³, *Z* = 4. With the use of 4693 unique reflections ($F_o > 6\sigma(F_o)$) collected at ca. 296 K with Mo Kα (λ = 0.7107 Å) radiation out to 2θ = 46° on a single crystal X-ray diffractometer, the structure was solved by standard direct and difference Fourier methods and refined by using 540 variables to a current value of the discrepancy index R_1 of 0.059. Atomic positional and thermal parameters are provided as supplementary material. Full details will be reported elsewhere.

(13) Elemental analysis: Calcd for Fe₂C₄₃H₄₁B₂Cl₃N₁₂O₉P₂(3·CHCl₃): Fe, 9.53; C, 44.09; H, 3.53; Cl, 9.08; N, 14.35; P, 5.29. Found: Fe, 9.28; C, 43.72; H, 3.50; Cl, 9.09; N, 14.44; P, 5.06.
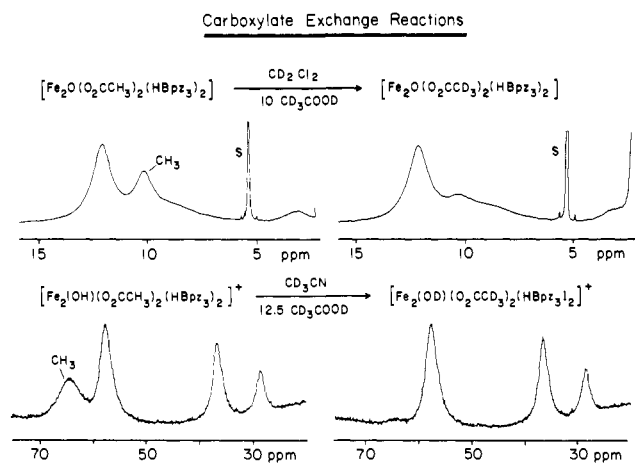
Figure 1. Carboxylate exchange reactions of **1** (top) and **2** (bottom) as monitored by ^{1}H NMR spectroscopy at 270 MHz. Assignments of the methyl (CH$_3$) resonances of the bridging acetate groups and the solvent (S) peaks in the top spectra are indicated.
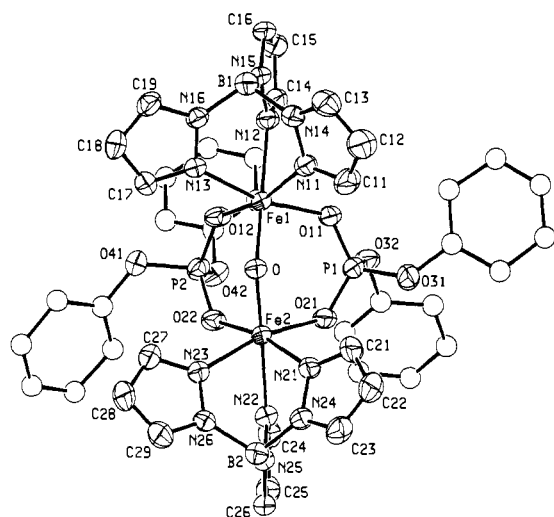

Figure 2. Structure of (μ-oxo)bis(μ-diphenylphosphato)bis{hydrotris(1-pyrazolyl)borato}diiron(III) (**3**) showing the 40% probability thermal ellipsoids and atom-labeling scheme. The phenyl ring carbon atoms are depicted as spheres with an arbitrary *B* value of 3.0 Å^2. For clarity, hydrogen atoms are omitted and the phenyl ring carbon atoms are not labeled. Selected interatomic distances (Å) and angles (deg) are as follows: Fe1–O 1.812 (5), Fe2–O 1.804 (5), Fe1–O11 2.059 (5), Fe1–O12 2.041 (5), Fe2–O21 2.045 (5), Fe2–O22 2.035 (5), Fe1–N11 2.137 (7), Fe1–N13 2.121 (6), Fe1–N12 2.213 (6), Fe2–N21 2.121 (6), Fe2–N23 2.142 (6), Fe2–N22 2.210 (7), Fe1···Fe2 3.337 (1), Fe1···P1 3.217 (2), Fe1···P2 3.210 (2), Fe2···P1 3.213 (2), Fe2···P2 3.205 (2), O11···O21 2.566 (7), O12···O22 2.576 (7), Fe1–O–Fe2 134.7 (3), O–Fe1–N12 179.8 (3), O–Fe2–N22 178.6 (2), N–Fe–N 81.0 (2)–85.3 (2).

observed in the structure of **1**.[1] The Fe···Fe distance of 3.337 Å and the Fe···P separations in the range 3.205–3.217 Å in **3** compare favorably with the corresponding distances of 3.36 and 3.27 Å determined by EXAFS measurements of a polynuclear Fe^{III}–ATP complex.[9]

Magnetic susceptibility measurements for a powdered sample of **3**[14] were made by using a SQUID-type susceptometer in the range 5–300 K. The data were well fit by the expression[15] for χ_M vs. *T* derived from the spin-exchange Hamiltonian, $H' = -2J\vec{S}_1 \cdot \vec{S}_2$, with $S_1 = S_2 = {}^5/_2$ and $g = 2.0$, $J = -98$ cm^{-1}.[16] This value for the antiferromagnetic exchange interaction constant is somewhat less negative than found for **1** ($J = -121$ cm^{-1}),[1] perhaps

owing to the slightly increased Fe–O$_{oxo}$ distances in **3** and/or the lesser contribution to the exchange coupling of phosphate compared to acetate. The effective magnetic moment of 1.87 μ_B per iron at 295 K in the solid state agrees well with the value of 1.91 μ_B measured for **3** in CD$_2$Cl$_2$ solution with use of an NMR method.[16] The electronic spectrum of **3**[16] bears a marked resemblance to that of **1** with the principal differences being a shift of the band at 699 nm in **1** (in CH$_2$Cl$_2$) to 624 nm in **3** and a sharp decrease for **3** in the intensity of the band at 492 nm in **1**. Resonances in the ^{1}H NMR spectrum of **3**[16] in CD$_2$Cl$_2$ solution fall in three regions. The pyrazolyl ring proton resonances occur between −10.9 and −13.8 ppm whereas the phenyl ring proton resonances fall in the range −7.15 to −7.9 ppm. The B–H signal is found at approximately −2.5 ppm. These magnetic and spectroscopic results establish the structural integrity of **3** in solution.

In conclusion, we have observed facile exchange of the bridging carboxylate ligands in **1** and demonstrated the synthetic utility of such a reaction by preparing the novel diphenylphosphate-bridged analogue **3**. This latter complex may be relevant to several naturally occurring Fe^{III}–phosphate systems. The ability to exchange ligands into the bridging positions of the {Fe$_2$O(bridge)$_2$}$^{2+}$ core is a significant discovery, affording a route to the synthesis of a variety of new compounds of chemical and biological interest.

(14) The sample used for susceptibility measurements was powdered and dried under vacuum, and it analyzes well for **3**·0.80 CHCl$_3$. Anal. Calcd for Fe$_2$C$_{42.8}$H$_{40.8}$B$_2$Cl$_{2.4}$N$_{12}$O$_9$P$_2$: C, 44.79; H, 3.58; Cl, 7.41; N, 14.65. Found: C, 44.38; H, 3.62; Cl, 7.42; N, 14.72.

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(16) Magnetic and spectroscopic data: IR (KBr cm^{-1}) 2500 (BH), 1594, 1491, 1088, 948; magnetic susceptibility, solid state [(*T*, K) μ_{eff}/Fe atom] (300) 1.89, (200) 1.46, (100) 0.79, (70) 0.46, (25) 0.03; solution (295 K, CD$_2$Cl$_2$) 1.91 μ_B per iron; UV–vis spectrum (CH$_2$Cl$_2$) λ 320 nm (ϵ_{Fe} 5830 cm^{-1} M^{-1}), 365 (5200), 478 sh (258), 624 (67); proton NMR spectrum (250 MHz, 295 K, CD$_2$Cl$_2$) δ 13.8, ~12.7 sh, ~10.9 sh, 7.9 sh, 7.37, 7.27, 7.15, ~2.5 (positive shifts are downfield of Me$_4$Si).

Total Synthesis of (+)-Compactin[1]

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Atherosclerosis is a condition in which abnormal amounts of lipids are deposited in certain arteries, resulting in intimal thickening. It manifests itself in circulatory occlusion, principally in the coronary, cerebral, and peripheral arteries. The ensuing complications lead to coronary heart disease, cerebrovascular disease, and some forms of peripheral vascular disease. These conditions are the major causes of death in the United States. In fact, the National Heart and Lung Institute Task Force on Arteriosclerosis reported in 1971 that approximately one-half of the deaths that occur in the United States each year are attributed to atherosclerosis.[2] It has long been known that there is a relationship between atherosclerosis and lipid metabolism. Since the condition results from abnormal deposition of lipids, there is

(1) Part 4 in the series "Synthetic and Biological Studies of Compactin and Related Compounds". For part 3, see: Rosen, T.; Taschner, M. J.; Heathcock, C. H. *J. Org. Chem.* **1985**, *50*, 1190.

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