reacting ³¹Si atoms were in their triplet ground state. The cyclization process involved a two-stage addition of the unpaired electrons in the triplet ³¹Si atoms to the conjugated π -bond systems of butadiene, each followed by a C-to-Si shift of H atoms. This is definitely a probable mechanism, and it should be responsible for the formation of the major portion of the observed SCPD* yields. However, other plausible mechanisms also may contribute to the SCPD* formation.

Let us turn to the recoil ${}^{11}C$ systems. For the reactions of ${}^{11}C$ atoms with alkenes, although π -bond interaction is always the predominant one. C-H insertion also contributes significantly to the product spectrum. In the case of C_2H_4 , π -bond interaction with ¹¹C atoms will produce center-labeled propadiene, as shown in (5), while C-H insertion by 11 C atoms will form end-labeled propadiene, as illustrated in (6).

$$^{11}C + CH_2 \longrightarrow \begin{bmatrix} ^{11}C \\ H_2C \longrightarrow CH_2 \end{bmatrix} \longrightarrow CH_2 \stackrel{11}{\longrightarrow} CH_2 \stackrel{11}{\longrightarrow} CH_2 = (5)$$

$${}^{1}C + CH_2 = CH_2 \rightarrow [{}^{1}CHCH = CH_2] \rightarrow {}^{1}CH_2 = C = CH_2 \quad (6)$$

Degradation of the ¹¹C-labeled propadiene demonstrated that about two-thirds of the propadiene was center labeled, but the other one-third had ¹¹C atoms on the end.^{18,19} Judging from this, and the expectation that there should be certain similarities in the reactions of C and Si atoms, it is likely that part of the SCPD* yields are also formed via a C-H insertion mechanism. As illustrated in eq 7, the C-H insertion by ³¹Si atoms in butadiene may be followed by an intramolecular π -bond addition process to give SCPD*. The formation of

$${}^{31}\mathrm{Si} + \underbrace{\overset{H}{\overset{H}}}_{C} \underbrace{\overset{H}{\overset{H}}}_{C} \underbrace{\overset{H}{\overset{G}}}_{C} \underbrace{\overset{Si}\mathrm{SiH}}_{H} \rightarrow \underbrace{\overset{Si}\mathrm{SiH}}_{H}^{2} (7)$$

SCPD* via two consecutive C-H insertion steps is probably less likely than the related mechanism as shown in (7).

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Specific Sequestering Agents for the Actinides. 3. Polycatecholate Ligands Derived from 2,3-Dihydroxy-5sulfobenzoyl Conjugates of Diaza- and Tetraazaalkanes¹

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Abstract: As part of a program to develop specific sequestering agents for the actinides, we have reported the synthesis of N, N', N'', N'''-tetra(2,3-dihydroxybenzoyl)tetraazacycloalkanes. These tetra(DHB) amides are potentially octadentate ligands via coordination of the catechol oxygen atoms. We now report the synthesis of the DHB amides of linear tetraaza- and diazaalkanes. Furthermore, sulfonation of these compounds in 20-30% SO3-H2SO4 yields exclusively their tetra(5-sulfo-DHB) analogues (2, 7, 10, 13). The sulfonated derivatives have several properties which make them superior to their precursors with respect to actinide coordination; these properties include increased water solubility, enhanced phenolic acidity, and improved oxidative stability near neutral pH. In vivo tests with mice have shown that tetrameric (5-sulfo-DHB) compounds (15, 18, 21) are generally acutely nontoxic, efficient sequestering agents for the actinides which promote rapid urinary excretion of ²³⁸Pu. Compound 21, the tetra(5-sulfo-DHB) derivative of spermine, is more effective than any other plutonium sequestering agent yet tested.

Introduction

The biological hazard presented by plutonium is a combination of its radioactivity and chemical properties.²⁻⁵ Plutonium is a potent carcinogen whose long-term retention in

mammals is due to the immobility of Pu(IV) in vivo. We are pursuing a biomimetic design concept to prepare new sequestering agents which will expedite plutonium removal and isolation.⁶ This approach is based on the observation that there are many chemical and biological similarities of Pu(IV) and



Figure 1. Quantitative, regiospecific 5-sulfonation of 1.

Fe(III). For example, in mammalian serum, Pu(IV) is bound and transported by the iron transport protein transferrin, where the Pu(IV) occupies the coordination site usually occupied by Fe(III).⁵

In microbes the transport of Fe(III) is accomplished by a class of low-molecular-weight complexing agents called siderophores.7 These typically incorporate hydroxamate and catecholate functional groups to form polychelate ligand which satisfy the six-coordinate geometry favored for Fe(III). We are preparing analogous tetracatechol ligands which can completely encapsulate the Pu(IV) ion and form the eightcoordinate geometry preferred by the actinide(IV) ions. We have recently reported this preferred geometry as it occurs in the structures of tetrakis(catecholato)thorate(IV) and -uranate(IV).¹ Furthermore, space-filling molecular models show that the attachment of four catechol groups to tetraazaalkanes gives compounds which can form octadentate cavities of the proper size for Pu(IV) and we have reported the preparation of 3,3,3,3-CYAM (14)^{6,9} and related compounds. Animal tests and titration studies indicated that the low solubility and weak acidity of the dihydroxybenzoyl (DHB) groups of 14 limited its potential as a Pu sequestering agent. In response to this, a further cycle of compound modification has been undertaken to prepare sulfonated derivatives in which -SO₃H groups are added to the DHB rings. This substantially improves the solubility, stability to air oxidation, and affinity for actinide(IV) ions at low pH. We next examined the effect of greater stereochemical freedom in an octadentate ligand by preparing tetra(5-sulfo-DHB) derivatives 18 and 21 of linear tetraamines. We have established that the equivalent quantity of the monomeric sulfonated dihydroxybenzamide from which the polychelate structure is derived (2, Figure 1) causes little if any Pu excretion. While further cycles of ligand modification and improvement are continuing (presently aimed at optimization of bridge length between monomeric units), test results for the Pu sequestering agents reported here show that at least one of the compounds is far superior to either diethylenetriaminepentaacetic acid (DTPA) or desferrioxamine B (DFOA)-the two agents presently used clinically in the treatment of human actinide poisoning.5 We report here a summary of the biological test results of these compounds which confirms our design concept for new actinide-ion-specific sequestering agents. The synthesis and characterization of the crystalline, dimeric 5-sulfo-DHB compounds are also included here to substantiate the synthetic procedures used for the tetramers and precursors, since the latter compounds are generally isolable only as amorphous, hydrated tetrasodium or -potassium salts.

Experimental Discussion

Chemical Background. As early as 1933 there were literature reports that stable, aqueous solutions of many metal ions—



Figure 2. Synthesis of dimeric 2,3-dihydroxy-5-sulfobenzamides and precursors.

including the actinides uranium and thorium—could be prepared at neutral pH using monomeric disulfonated aromatic o-dihydroxy compounds as ligands.⁸ With this in mind we have focused upon the preparation of the tetrameric 5-sulfo-2,3dihydroxybenzamides (CAMS),9 which are potentially octadentate ligands for the actinides in which the lengths of the joining methylene bridges help determine the metal specificity. All tetra-2,3-dihydroxybenzamide (CAM) precursors were prepared using the general procedures reported earlier.⁶ Their direct sulfonation was accomplished at room temperature with 20-30% SO₃-H₂SO₄-which serves as both solvent and reactant.¹⁰ The sulfonation products were isolated at pH 4 as their hydrated tetrasodium or -potassium salts. Both elemental analysis and pH-titration to obtain neutralization equivalents proved that monosulfonation of each catechol unit occurred. Model experiments in SO_3 - H_2SO_4 indicated (by inference) regiospecific sulfonation at the 5 position resulting in isomerically pure LICAMS compounds. For example, a ¹H NMR of 2,3-dihydroxy-N,N-dimethylbenzamide (1) dissolved in 20% SO₃-H₂SO₄ showed an AB quartet in the aromatic region with $J_{AB} = 2$ Hz. This portion of the spectrum was superimposable upon that of 5-sulfo-2,3-dihydroxybenzenesulfonic acid (3), also in H₂SO₄ solution, indicating that quantitative monosulfonation in the 5 position had occurred (Figure 1). This regiospecific 5-sulfonation was also shown for three dimeric compounds (7, 10, and 13) (Table I, Figure 2).

Design Concept and Ligand Evaluation. Our goal has been the synthesis of tetrameric catechoylamide (CAM) ligands which will effect complete encapsulation of a Pu(IV) ion through coordination of the eight catechol oxygens—and do so without significant coordination of other metal ions that are present in vivo. This has so far proceeded in three distinct steps.

The first step in this program was the synthesis of a series of tetracatechol ligands on both linear and cyclic tetraamines as platforms. The tetracatechols are indeed much more effective sequestering agents than is the equivalent coordination by four of the monomeric catechol ligands.

The second step in this program was the optimization of the ligand geometry. We have determined that the preferred coordination geometry is that of the D_{2d} trigonal-faced dodecahedron¹¹ for the tetrakis(catecholato) complexes of U(IV), Th(IV), Ce(IV), and Hf(IV).^{1,12} We have also found that the linear tetraamine platform constructs more effective chelating agents than the corresponding cyclic tetraamine platform. This apparently is due to the greater stereochemical freedom of the linear platform-which must be more important than the predisposition toward the metal-ion-encapsulating geometry that the cyclic platform imposes upon the tetracatechol ligand. Finally, the size of the central cavity formed by the four appended catechol groups can be adjusted by changing the number of bridging methylene units in the linear tetraamine platform. The optimum geometry is achieved when the central bridge is butylene (m = 4 in Figure 4) and the

Table I. Dimeric 2,3-Dihydroxy-5-sulfobenzamides and Precursors







terminal bridges are propylene (n = 3); this is the natural product spermine.

The third step in this program has been the modification of the substituent catechol rings by sulfonation. This results in tetracatechol chelating agents which are very water soluble, are more effective complexing agents at lower pH owing to their great acidity, and are relatively stable to air oxidation. The most effective sequestering agent yet produced is **21** (3,4,3-LICAMS), for which test studies with mice have resulted in 65% removal of ²³⁸Pu with one administration of ligand under conditions where an equimolar amount of CaNa₃ DTPA gives 63% removal. However, at lower concentrations of ligand 3,3,4-LICAMS is up to 100 times as effective as an equivalent concentration of CaNa₃ DTPA. Perhaps more important, 3,4,3-LICAMS removes some ²³⁸Pu already deposited in the skeleton—the skeletal ²³⁸Pu was reduced to 0.22 of the 1-h control value.¹³

Experimental Section

Melting points were taken on a Buchi apparatus in open capillaries and are uncorrected. Infrared spectra (KBr disks) were recorded on a Perkin-Elmer 283 instrument. ¹H NMR spectra (D₂O) were recorded on a Varian T-60 or Varian A-60 instrument using 3-trimethylsilyl-1-propanesulfonic acid sodium salt hydrate as internal standard. Evaporations were accomplished (40-60 °C) with a Buchi Rotovapor-RE. Microanalyses were performed by Analytical Services, Chemistry Department, University of California, Berkeley. The sulfonated products (15 and 21) were dried at 120 °C (0.1 mmHg) in vacuo; the sulfonated compounds (2, 7, 10, and 13) were dried at room temperature in a vacuum desiccator over P2O5/NaOH pellets prior to elemental analysis. The ion exchange resin used in the synthesis of 2 was Bio-Rad, AG50W-X² (50-100 mesh). The alumina used in the chromatography of precursors 16 and 19 was CAMAG basic, in a $15 \times \frac{3}{4}$ in. o.d. column. The appropriate diaza- and tetraazaalkanes were used in the synthesis of each LICAM according to the two-step general procedure (Figure 2) we have earlier used to prepare pre-



Figure 4. Structural formulas of catechoylamides formed from linear tetraamines.

cursors 1,5,9,13-N,N',N'',N''',tetra(2,3-dihydroxybenzoyl)tetraazacyclohexadecane (14, 3,3,3,3-CYCAM⁶) and 1¹⁴ (Figure 1). The tetraazaalkanes, spermine (amine component of 21) and N,N'bis(4-aminobutyl)-1,4-butanediamine (amine component of 18), were purchased from Ames Laboratory, Inc., Milford, Conn. Reagent 3, 4,5-dihydroxy-*m*-benzenedisulfonic acid disodium salt (Figure 1), was obtained from Eastman Kodak Co., Rochester, N.Y. Reagent 4 (2,3-dimethoxybenzoyl chloride, Figure 2) was prepared from an equivalent amount of the corresponding acid by treatment with excess SOCl₂ for 3 h at room temperature followed by coevaporation with CCl₄ to the crystalline, crude acid chloride and was used without further purification.

N,N-Dimethyl(2,3-dihydroxy-5-sulfo)benzamide (2). Solid 1 (1.3 g, 7.2 mmol) dissolved in 30% fuming H_2SO_4 (10 mL) was allowed to stand overnight in a stoppered flask immersed in a water bath (22 °C). A ¹H NMR of a reaction mixture aliquot revealed only an AB quartet $(J_{AB} = 2 \text{ Hz})$ in the aromatic region. This reaction solution was poured onto ice, resulting in a clear aqueous solution (100 mL). Careful dropwise addition of 10 N NaOH, with vigorous stirring and (ice water bath) cooling, gave a pH 4 solution at ambient temperature. Additon of 1 volume of MeOH precipitated the inorganic salt, which was removed by filtration, washed well with MeOH-H₂O (1:1 v/v), then discarded. The combined filtrate and wash were evaporated to a solid, redissolved in H_2O , and eluted from a 100-mequiv H⁺ ion exchange column. Fractions containing 2 were identified by a (blue) color test with FeCl₃ solution. These were evaporated to a residue and dried in a vacuum desiccator at room temperature over P2O5/NaOH to yield the hygroscopic, white solid 2.2.5H₂O (2.0 g, 94%): mp 143-145 °C; IR 2500-3700 (>CH, -OH), 1670 (-CON<), 1600, 1465, 1410, 1385, 1210 (SO₃⁻), 1160 (SO₃⁻), 1100, 1040, 610 $(SO_3^-) \text{ cm}^{-1}$; NMR δ 2.97 [broad s, 6 H, -CON(CH₃)₂], 7.20 (d, 1 H, 4-ArH, $J_{AB} = 2$ Hz), 7.37 (d, 1 H, 6-ArH, $J_{AB} = 2$ Hz).

Anal. Calcd for C₉H₁₁NO₆S-2.5 H₂O: N, 4.59; S, 10.50. Found: N, 4.45; S, 10.55.

N,N'-Bis(2,3-dimethoxybenzoyl)-1,4-diazabutane (5). To 2,3dimethoxybenzoyl chloride (4, 34.3 mmol), dissolved in N,N-dimethylacetamide (DMAA, 20 mL), were added ethylenediamine (1.0 g, 17 mmol) and NEt₃ (3.5 g, 34.6 mmol) in DMAA (30 mL) solution. The combined ingredients were stirred in a stoppered flask immersed in a 60 °C oil bath for 20 h. After evaporation to a residue, the product Anal. Calcd for $C_{20}H_{24}N_2O_6$: C, 61.84; H, 6.23; N, 7.21. Found: C, 61.55; H, 6.621; N, 7.09.

N,N'-Bis(2,3-dihydroxybenzoyl)-1,4-diazabutane (2-LICAM, 6). Under argon a solution of **5** (5.0 g, 13 mmol) in CH₂Cl₂ (40 mL) was added dropwise to a solution of BBr₃ (6.5 mL, 68 mmol) in CCl₄ (75 mL). During the addition, the latter solution was vigorously stirred while immersed in a room temperature water bath. An immediate precipitate formed and was allowed to stir overnight. Addition of 50 mL of H₂O (*Caution*: HBr evolution) followed by a 2-h pause for completion of hydrolysis resulted in a crude white solid which was collected by filtration and washed well with H₂O to remove acids. Recrystallization of the crude white solid from aqueous MeOH gave $6\cdot1H_2O$ (3.85 g, 95%), mp 214-217 °C.

Anal. Calcd for C₁₆H₁₆N₂O₆·1H₂O: C, 54.86; H, 5.18; N, 8.00. Found: C, 54.85; H, 5.20; N, 8.02.

N,N'-Bis(2,3-dihydroxy-5-sulfobenzoyl)-1,4-diazabutane (2-LI-CAMS, 7). In portions, 4.5 g (13.5 mmol) of 6 was added to 20% fuming H₂SO₄ (50 mL) contained in a stoppered round-bottom flask which was immersed in a 22 °C water bath, while stirring vigorously with a magnetic stir bar. The reaction solution sat overnight and was then carefully poured onto ice. The resulting solid was collected by filtration or centrifugation. Recrystallization from minimum hot H₂O, followed by filtration in an ice water wash, and drying overnight in a vacuum desiccator over P₂O₅ gave 7-4H₂O (3.3 g, 43%): mp 259-260 °C dec; IR 2500-3700 (>CH, OH), 1640 (-CON<), 1590, 1555, 1480, 1425, 1280, 1275 (SO₃⁻), 1165 (SO₃⁻), 1035, 610 (SO₃⁻), cm⁻¹; NMR δ 3.72 (broad s, 4 H, -CH₂CH₂-), 7.52 (d, 2 H, 4-ArH, J_{AB} = 2 Hz), 7.82 (d, 2 H, 6-ArH, J_{AB} = 2 Hz).

Anal. Calcd for $C_{16}H_{16}N_2O_{12}S_2\text{-}4H_2O\text{-}C,\,34.04;\,H,\,4.29;\,N,\,4.96;\,S,\,11.36.$ Found: C, 33.88; H, 4.37; N, 4.69; S, 11.70.

N,*N'*-**Bis(2,3-dimethoxybenzoyl)-1,6-diazahexane (8).** Using the same procedure as in the synthesis of 5, the following ingredients were combined: 4 (38.4 mmol); 1,4-butanediamine dihydrochloride (3.06 g, 19 mmol); NEt₃ (7.8 g, 77 mmol); DMAA (60 mL). Workup and recrystallization from 95% EtOH gave 8 (4.3 g, 55%), mp 143–145 °C.

Anal. Calcd for $C_{22}H_{28}N_2O_6;\,C,\,63.45;\,H,\,6.78;\,N,\,6.73.$ Found: C, 63.06; H, 6.75; N, 6.62.

N,N'-Bis(2,3-dihydroxybenzoyl)-1,6-diazahexane (4-LICAM, 9). Using the procedure as in the synthesis of 6, the following ingredients were combined: 8 (4.0 g, 9.6 mmol); BBr₃ (5.0 mL, 53 mmol); CH₂Cl₂ (115 mL). Workup and recrystallization from H₂O/MeOH gave 9 (3.2 g, 91%), mp 203-205 °C.

Anal. Cated for C₁₈H₂₆N₂O₆: C, 59.99; H, 5.59; N, 7.77. Found: C, 59.76; H, 5.73; N, 7.68.

N,*N'*-**Bis**(2,3-dihydroxy-5-sulfobenzoyl)-1,6-diazahexane (4-LICAMS, 10). Using the same procedure as in the synthesis of 7, the following reactants were combined: 9 (3.1 g, 8.6 mmol); 20% fuming H₂SO₄ (30 mL). Workup and recrystallization from H₂O gave 10-2H₂O (2.0 g, 42%): mp 256.5-257.5 °C dec; IR 2500-3700 (\geq CH, -OH), 1650 (-CON<), 1595, 1550, 1470, 1430, 1330, 1280, 1225 (SO₃⁻), 1160 (SO₃⁻), 1110, 1040, 610 (SO₃⁻) cm⁻¹; NMR δ 1.6-2.0 (broad, 4 H, -CH₂CH₂NH-), 3.3-3.8 (broad, 4 H, -CH₂CH₂NH-), 7.57 (d, 2 H, 4-ArH, J_{AB} = 2 Hz). 7.87 (d, 2 H, 6-ArH, J_{AB} = 2 Hz).

Anal. Calcd for C₁₈H₂₀N₂O₁₂S₂·2H₂O: C, 38.85; H, 4.35; N, 5.03; S, 11.52. Found: C, 38.79; H, 4.59; N, 4.99; S, 11.45.

N,N'-Bis(2,3-dimethoxybenzoyl)-1,8-diazaoctane (11). Using the same procedure as in the synthesis of 5, the following reactants were combined: 4 (40 mmol); NEt₃ (4.05 g, 40 mmol); 1,6-hexanediamine (2.32 g, 20 mmol); DMAA (60 mL). Workup and recrystallization from 95% EtOH gave 11 (8.46 g, 95%), mp 137-139 °C.

Anal. Calcd for $C_{24}H_{32}N_2O_6$: C, 64.83; H, 7.25; N, 6.30. Found: C, 64.40; H, 7.28; N, 6.06.

N,N'-Bis(2,3-dihydroxybenzoyl)-1,8-diazaoctane (6-LICAM, 12). Using the same procedure as in the synthesis of 6, the following reagents were combined: 11 (6.7 g, 15 mmol) in CH₂Cl₂ (60 mL); BBr₃ (7.5 mL, 79 mmol) in CH₂Cl₂ (75 mL). Workup and recrystallization from H₂O/MeOH gave 12 (4.2 g, 85%), mp 214-217 °C.

Anal. Calcd for $\tilde{C}_{20}H_{24}N_2O_6$; C, 61.84; H, 6.23; N, 7.21. Found: C, 61.56; H, 6.23; N, 7.09.

N,N'-Bis(2,3-dihydroxy-5-sulfobenzoyl)-1,8-diazaoctane (6-LI-

CAMS, 13). Using the same procedure as in the synthesis of 7, the following reagents were combined: **12** (4.5 g, 11.5 mmol); 30% fuming H₂SO₄ (45 mL). Workup and recrystallization from H₂O gave **13**-2H₂O (3.2 g, 48%): mp 253-254 °C dec; IR 2500-3700 (>CH, -OH), 1640 (-CON<), 1590, 1550, 1425, 1280, 1215 (SO₃⁻⁻), 1165 (SO₃⁻⁻), 1105, 1040, 610 (SO₃⁻⁻) cm⁻¹; NMR δ 1.2-1.9 [broad, 8 H, -(CH₂)₄CH₂NH-], 3.2-3.6 [broad, 4 H, -(CH₂)₄CH₂NH-], 7 60 (d, 2 H, 4-ArH, J_{AB} = 2 Hz), 7.92 (d, 2 H, 6-ArH, J_{AB} = 2 Hz). Anal. Calcd for C₂₀H₂₄N₂O₁₂S₂·2H₂O; C, 41.09; H, 4.83; N, 4.79;

S, 10.97. Found: C, 41.41; H, 5.07; N, 4.78; S, 11.21.

N.N',N",N"'-Tetra(2,3-dihydroxy-5-sulfobenzoyl)-1,5,9,13tetraazacyclohexadecane Tetrasodium Salt (3,3,3,3-CYCAMS, 15). Crude, dry precursor 3,3,3,3-CYCAM (14, 1.0 g, 1.2 mmol) dissolved in 30% fuming H₂SO₄ (10 mL) sat overnight in a stoppered flask immersed in a 22 °C water bath. The reaction solution was poured onto ice, resulting in a clear (100 mL) solution. Careful addition of 10 N NaOH, with vigorous stirring and ice-water cooling, gave a pH 4 solution at ambient temperature. Addition of 1 volume of MeOH provided a copious inorganic precipitate which was removed by filtration and discarded after washing well with 1:1 H₂O/MeOH. (A portion of this filtrant gave no blue color in the presence of aqueous FeCl₃.) The combined filtrate and wash was evaporated to dryness and then redissolved in minimum H2O. Careful addition of MeOH, then EtOH, and finally Et₂O (to give substantial turbidity) followed by filtration gave a clear, nearly colorless solution. Subsequent addition of 2-3 volumes of Et₂O gave a white solid; this was isolated by filtration, washed well with Et_2O , then dried at 120 ° (<0.1 mmHg) overnight. Thus was obtained hygroscopic 15.5H2O (1.4 g, 92%): IR 2800-3700 (>CH, -OH), 1610 (-CON<), 1485, 1410, 1250-1140 (SO_3^-) , 1100, 1045, 615 (SO_3^-) cm⁻¹; NMR δ 1.6–2.6 (broad, 8 H, -CH2CH2N<), 2.8-4.2 (broad, 16 H, -CH2N<), 7.0-8.0 (complex m, 7 H, ArH); purity also established by pH titration giving pK_{a_1} , = 8.12 (4 protons) and $pK_{a_2} = 12.0$ (4 protons) for the four catechol groups

Anal. Calcd for $C_{40}H_{40}N_4O_{24}Na_4\cdot 5H_2O$: C, 37.80; H, 3.96; N, 4.41; S, 10.09; Na, 7.23. Found: C, 37.52; H, 3.94; N, 4.39; S, 9.74; Na, 7.60.

N,N',N'',N'''. Tetra(2,3-dihydroxy-5-sulfobenzoyl)-1,6,11,16tetrahexadecane Tetrasodium Salt (4,4,4-LICAMS, 21). Using the same procedure as in the synthesis of 5, the following materials were combined: 4 (35 mmol); 1,6,11,16-tetraazahexadecane (2.0 g, 8.7 mmol); NEt₃ (3.54 g, 35 mmol); DMAA (40 mL). The reaction mixture was evaporated to residual oil which was partitioned between H₂O/CHCl₃. Next the CHCl₃ layer was washed well with aqueous HCl, H₂O, then aqueous NaOH before drying with MgSO₄ and elution from an alumina column with mixtures of 0-5% EtOH in CH₂Cl₂. Column fractions were monitored with TLC. Thus was obtained the tetra(2,3-dimethoxybenzoyl) precursor (16) as a glassy solid (6.6 g, 86%): IR 3400 (-NHCO), 2940 (>CH), 1655 and 1635 (>NCO-) cm⁻¹. This material was used in the next step.

Anal. Calcd for C₄₈H₆₂N₄O₁₂: C, 64.99; H, 7.05; N, 6.32. Found: C, 65.18; H, 6.82; N, 6.23.

Using the same procedure as in the synthesis of 6, the following materials were combined: compound 16 (3.7 g, 4.2 mmol); BBr₃ (4 mL, 42 mmol); CH₂Cl₂ (115 mL). After hydrolysis with H₂O (50 mL), the crude product was collected by filtration and washed well with H₂O to remove acids, then with Et₂O, and dried in a vacuum desiccator over P₂O₅/NaOH (pellets) to obtain crude, dry 4,4,4-LICAM (17, 2.1 g, ~62%), which was satisfactory for use in the next step.

The dry, crude 17 (1.0 g, 1.2 mmol) was sulfonated and isolated precisely as in the synthesis of 15 to obtain hygroscopic, white solid 18·4H₂O·1/4Na₂SO₄ (1.4 g, 88%): IR 2800-3700, 1600 (>NCO-), 1475, 1150-1300 (SO₃⁻), 1100, 1045, 620 (SO₃⁻) cm⁻¹; NMR δ 1.3-2.1 (broad, 12 H, -CH₂CH₂CH₂N<), 2.8-3.8 (broad, 12 H, -CH₂N<), 7.2-8.0 (complex m, 8 H, ArH). pH titration gave pK_{a1} = 7.49 (4 protons), pK_{a2} = 12.10 (4 protons), for four catechol units

Anal. Calcd for $C_{40}H_{42}N_4O_{24}S_4Na_4\cdot 4H_2O_{4}Na_2SO_4$: C, 37.22; H, 3.91; N, 4.34; S, 10.56; Na, 8.02. Found: C, 37.27; H, 4.02; N, 4.51; S, 10.87; Na, 8.42.

N,N',N'',N'''-Tetra(2,3-dihydroxy-5-sulfobenzoyl)-1,5,10,14-tetraazatetradecane Tetrasodium Salt (3,4,3-LICAMS, 21). Using the same procedure as in the synthesis of 5, the following materials were combined: spermine (2.0 g, 9.9 mmol); 4 (40 mmol); NEt₃ (4.05 g, 40 mmol); DMAA (40 mL). Evaporation of the reaction mixture gave an oily residue which was partitioned between H₂O/CH₂Cl₂. Purification of this crude product in CH2Cl2 solution was accomplished as in the synthesis of 16. In this way a 4-g fraction of the tetra(2,3dimethoxybenzoyl) compound, 19, was obtained for use in the next step.

Using the same procedure as in the synthesis of 6, the following reagents were combined: precursor 19 (4 g, 4.6 mmol); BBr₃ (4.2 mL, 44 mmol); CH₂Cl₂ (115 mL). Hydrolysis (50 mL, H₂O), filtration, and thorough water wash, then vacuum drying at room temperature over P2O5/NaOH pellets, gave crude 3,4,3-LICAM (20, 3 g), satisfactory for the sulfonation step.

As in the synthesis of 19, the following reagents were combined: 20 (2.5 g, 3.3 mmol) and 3% fuming H₂SO₄ (30 mL). After pouring on ice, then neutralization with 10 N NaOH to pH 4 and subsequent workup as for 18, hygroscopic, white solid 21.6.5H₂O (2.1 g, 50%) was obtained: IR 3700-2500 (>CH, -OH), 1640-1590 (-CON<), 1470, 1420, 1380, 1210-1180 (SO₃⁻), 1100, 1040, 615 (SO₃⁻) cm⁻¹; NMR δ 1.3-2.3 (broad, 8 H, -CH₂CH₂N<), 2.8-3.8 (broad, 12 H, -CH₂N<), 7.1-7.9 (broad m, 8 H, ArH).

Anal. Calcd for $C_{38}H_{38}N_4O_{24}S_4Na_{4}\cdot 6.5H_2O$ (variable water content): C, 35.88; H, 4.04; N, 4.40; S, 10.08; Na, 7.23. Found: C, 36.38; H, 3.73; N, 4.24; S, 9.26; Na, 7.13.

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- The structures, as well as our abbreviated nomenclature for some of the (9) title compounds, appear in Table I. For IUPAC names see Experimental Section. Our system of abbreviation, based on CAM as an acronym for catechoylamide, uses prefixes CY and LI to indicate a cyclic or linear compound, respectively. The numbers in the prefix indicate the length of the methylene chains connecting the CAM moleties and, should letters appear in the prefix, they indicate N-terminal substituents in a linear compound. The suffix indicates substituents on each benzene ring of the CAM ligand.
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- (11) The two highest symmetry coordination geometries for eight coordination are D_{4d} (Archimedian antiprism) or D_{2d} (trigonal-faced dodecahedron). We have found the latter in the $[Ac(cat)_4]^{4-}$ structures (see ref 1 and 12).
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Preparation, Physical Properties, and X-ray Structure of the Mixed-Valence Compound Diferrocenylselenium Iodine Triiodide Hemi(methylene chloride)

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Abstract: Diferrocenyl selenide is oxidized by iodine in dichloromethane to give a mixed-valence compound. The structure of $\{[Fe(\eta^5-C_5H_5)(\eta^5-C_5H_4)]_2Se|I_3-I_2-I_2CH_2C|_2 \text{ has been determined using heavy-atom methods in conjunction with least$ squares refinement of data measured on a four-circle X-ray diffractometer. The compound crystallizes with triclinic symmetry with two formula weights in a cell having the dimensions a = 11.647 (5) Å, b = 11.519 (5) Å, c = 10.633 (5) Å, $\alpha = 97.65$ (4)°, $\beta = 95.73$ (4)°, $\gamma = 88.10$ (4)°, and V = 1406.5 Å³. The observed and calculated densities are 2.60 and 2.658 g cm⁻³, respectively. The structure was refined using 3582 observed reflections (graphite-monochromated Mo K α) to give conventional discrepancy factors of R = 0.0616 and $R_w = 0.0654$. Discrete mixed-valence [Fe(η^5 -C₅H₅)(η^5 -C₅H₄)]₂Se⁺ cations and an anion structure consisting of zigzag chains of triiodide anions and iodine molecules are present. The mixed-valence bridged ferrocene cation assumes a gauche conformation intermediate between the cisoid and transoid conformations. The distance between the two iron ions is 6.058 (2) Å. As indicated by the centroid-to-centroid ring distances, the two $Fe(\eta^5-C_5H_5)(\eta^5-C_5H_4)$ moieties are structurally different. One is a ferrocenyl group, the other a ferricenyl group. The localized nature of the mixedvalence cation is substantiated by 57Fe Mössbauer spectra, which show two quadrupole-split doublets. EPR data are inconclusive, whereas IR spectra also point to a localized electronic structure. No intervalence transfer band is seen in the near-IR region of the electronic absorption spectrum of this compound and it is concluded that it is a class I mixed-valence species.

Introduction

Mixed-valence compounds contain ions of the same element in two different oxidation states.³⁻⁶ The study of mixed-valence compounds will potentially aid in understanding electron transfer as found in oxidation-reduction, electrochemical, and biological processes. There is a growing interest in the lowenergy electronic absorption band, the so-called intervalence band, exhibited by mixed-valence compounds. A detailed analysis of this absorption band could provide information about thermal electron transfer.7-9

Bridged ferrocenes have proven to be good candidates for mixed-valence compounds owing to their variability in structure and suitability for study with several physical techniques such as ⁵⁷Fe Mössbauer spectroscopy and EPR.^{10,11} By employing the intrinsic time scales associated with various physical techniques, it has been possible to bracket the thermal electron-transfer rates for the mixed-valence bridged ferro-