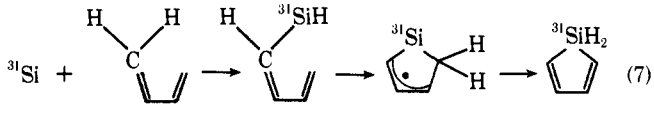
reacting ^{31}Si atoms were in their triplet ground state. The cyclization process involved a two-stage addition of the unpaired electrons in the triplet ^{31}Si atoms to the conjugated π-bond systems of butadiene, each followed by a C-to-Si shift of H atoms. This is definitely a probable mechanism, 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 ^{11}C 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).

$$^{11}C + CH_2{=}CH_2 \longrightarrow \left[\begin{array}{c} {}^{11}C \\ / \quad \backslash \\ H_2C{-}CH_2 \end{array}\right] \longrightarrow CH_2{=}{}^{11}C{=}CH_2 \quad (5)$$

$$^{11}C + CH_2{=}CH_2 \rightarrow [{}^{11}CHCH{=}CH_2] \rightarrow {}^{11}CH_2{=}C{=}CH_2 \quad (6)$$

Degradation of the ^{11}C-labeled propadiene demonstrated that about two-thirds of the propadiene was center labeled, but the other one-third had ^{11}C 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 ^{31}Si atoms in butadiene may be followed by an intramolecular π-bond addition process to give SCPD*. The formation of



(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-5-sulfobenzoyl Conjugates of Diaza- and Tetraazaalkanes[1]

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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% SO_3–H_2SO_4 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 ^{238}Pu. 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

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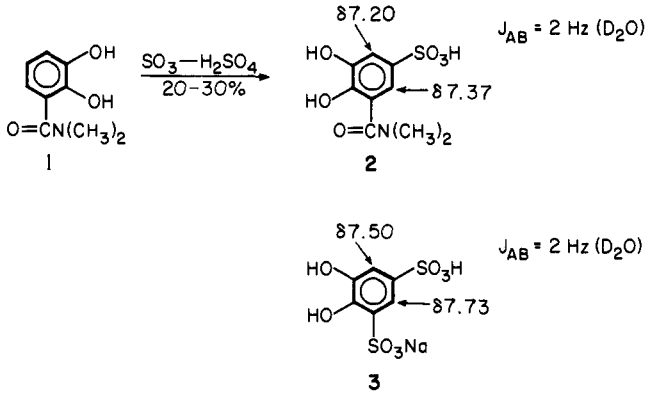


Figure 1. Quantitative, regiospecific 5-sulfonation of **1**.

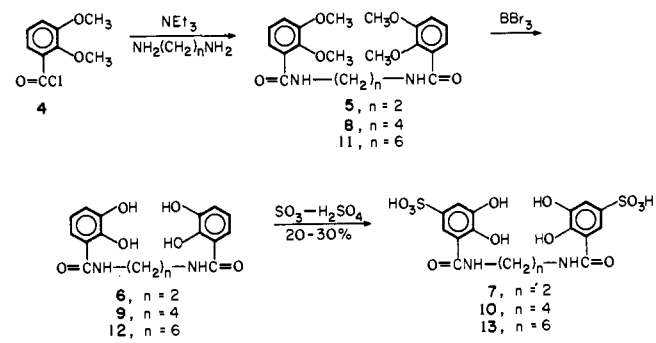


Figure 2. Synthesis of dimeric 2,3-dihydroxy-5-sulfobenzamides and precursors.

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 eight-coordinate 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 $-SO_3H$ 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

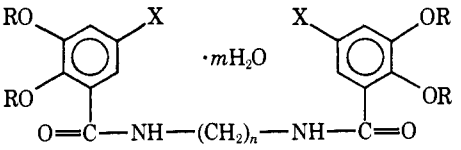
Chemical Background. As early as 1933 there were literature reports that stable, aqueous solutions of many metal ions—including the actinides uranium and thorium—could be prepared at neutral pH using monomeric disulfonated aromatic *o*-dihydroxy compounds as ligands.[8] With this in mind we have focused upon the preparation of the tetrameric 5-sulfo-2,3-dihydroxybenzamides (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% $SO_3-H_2SO_4$—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% $SO_3-H_2SO_4$ 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 H_2SO_4 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.

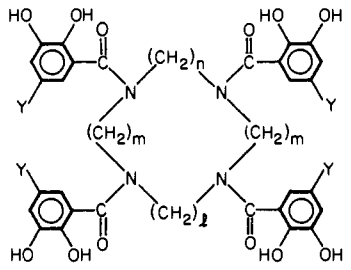
The first step in this program was the synthesis of a series of tetracatechol ligands on both linear and cyclic tetraamines as platforms. The tetracatechols are indeed much more effective sequestering agents than is the equivalent coordination by four of the monomeric catechol ligands.

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 dodecahedron[11] 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

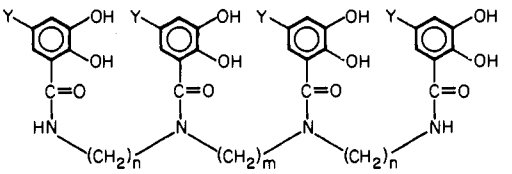


compd	*n*	*m*	X	R	mp, °C (recrystn solvent)	yield, %	abbreviated name
5	2	0	H	CH_3	140–142 (95% EtOH)	92	
6	2	1	H	H	214–217 ($MeOH/H_2O$)	85	2-LICAM·H_2O
7	2	4	SO_3H	H	259–260 dec (H_2O)	43	2-LICAMS·$4H_2O$
8	4	0	H	CH_3	143–145 (95% EtOH)	55	
9	4	0	H	H	203–206 ($MeOH/H_2O$)	91	4-LICAM
10	4	2	SO_3H	H	256.5–257.5 dec (H_2O)	42	4-LICAMS·$2H_2O$
11	6	0	H	CH_3	137–139 (95% EtOH)	95	
12	6	0	H	H	186–188 ($MeOH/H_2O$)	85	6-LICAM
13	6	2	SO_3H	H	253–254 dec (H_2O)	48	6-LICAMS·$2H_2O$



14, n = m = *l* = 3; Y = H
15, n = m = *l* = 3; Y = SO_3Na

Figure 3. Structural formulas of catechoylamides formed from cyclic tetraamines.



17, n = m = 4; Y = H
18, n = m = 4; Y = SO_3No
20, n = 3; m = 4; Y = H
21, n = 3; m = 4; Y = SO_3Na

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

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 ^{238}Pu with one administration of ligand under conditions where an equimolar amount of $CaNa_3$ 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 $CaNa_3$ DTPA. Perhaps more important, 3,4,3-LICAMS removes some ^{238}Pu already deposited in the skeleton—the skeletal ^{238}Pu 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 (D_2O) 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 $P_2O_5/NaOH$ pellets prior to elemental analysis. The ion exchange resin used in the synthesis of **2** was Bio-Rad, AG50W-X^2 (50–100 mesh). The alumina used in the chromatography of precursors **16** and **19** was CAMAG basic, in a 15 × ¾ 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 precursors 1,5,9,13-*N,N′,N″,N‴*-tetra(2,3-dihydroxybenzoyl)tetraazacyclohexadecane (**14,** 3,3,3,3-CYCAM[6]) and **1**[14] (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 $SOCl_2$ for 3 h at room temperature followed by coevaporation with CCl_4 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 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–H_2O (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 $FeCl_3$ solution. These were evaporated to a residue and dried in a vacuum desiccator at room temperature over $P_2O_5/NaOH$ to yield the hygroscopic, white solid **2**·$2.5H_2O$ (2.0 g, 94%): mp 143–145 °C; IR 2500–3700 (>CH, -OH), 1670 (-CON<), 1600, 1465, 1410, 1385, 1210 (SO_3^-), 1160 (SO_3^-), 1100, 1040, 610 (SO_3^-) cm^{-1}; NMR δ 2.97 [broad s, 6 H, $-CON(CH_3)_2$], 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 $C_9H_{11}NO_6S$·2.5 H_2O: N, 4.59; S, 10.50. Found: N, 4.45; S, 10.55.

***N,N′*-Bis(2,3-dimethoxybenzoyl)-1,4-diazabutane (5).** To 2,3-dimethoxybenzoyl chloride (**4**, 34.3 mmol), dissolved in *N,N*-dimethylacetamide (DMAA, 20 mL), were added ethylenediamine (1.0 g, 17 mmol) and NEt_3 (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

mixture was triturated with water and collected by filtration. Crude product was washed well with dilute aqueous NaOH and HCl. Recrystallization from 95% EtOH gave **5** (6.2 g, 92%), mp 141–143 °C.

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 CH_2Cl_2 (40 mL) was added dropwise to a solution of BBr_3 (6.5 mL, 68 mmol) in CCl_4 (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 H_2O (*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 H_2O to remove acids. Recrystallization of the crude white solid from aqueous MeOH gave **6**·$1H_2O$ (3.85 g, 95%), mp 214–217 °C.

Anal. Calcd for $C_{16}H_{16}N_2O_6$·$1H_2O$: 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-LICAMS, 7).** In portions, 4.5 g (13.5 mmol) of **6** was added to 20% fuming H_2SO_4 (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 H_2O, followed by filtration in an ice water wash, and drying overnight in a vacuum desiccator over P_2O_5 gave **7**·$4H_2O$ (3.3 g, 43%): mp 259–260 °C dec; IR 2500–3700 (>CH, OH), 1640 (-CON<), 1590, 1555, 1480, 1425, 1280, 1275 (SO_3^-), 1165 (SO_3^-), 1035, 610 (SO_3^-) cm^{-1}; NMR δ 3.72 (broad s, 4 H, $-CH_2CH_2-$), 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 $C_{16}H_{16}N_2O_{12}S_2$·$4H_2O$: 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); NEt_3 (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); BBr_3 (5.0 mL, 53 mmol); CH_2Cl_2 (115 mL). Workup and recrystallization from H_2O/MeOH gave **9** (3.2 g, 91%), mp 203–205 °C.

Anal. Calcd for $C_{18}H_{26}N_2O_6$: 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 H_2SO_4 (30 mL). Workup and recrystallization from H_2O gave **10**·$2H_2O$ (2.0 g, 42%): mp 256.5–257.5 °C dec; IR 2500–3700 (>CH, -OH), 1650 (-CON<), 1595, 1550, 1470, 1430, 1330, 1280, 1225 (SO_3^-), 1160 (SO_3^-), 1110, 1040, 610 (SO_3^-) cm^{-1}; NMR δ 1.6–2.0 (broad, 4 H, $-CH_2CH_2NH-$), 3.3–3.8 (broad, 4 H, $-CH_2CH_2NH-$), 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 $C_{18}H_{20}N_2O_{12}S_2$·$2H_2O$: 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); NEt_3 (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 CH_2Cl_2 (60 mL); BBr_3 (7.5 mL, 79 mmol) in CH_2Cl_2 (75 mL). Workup and recrystallization from H_2O/MeOH gave **12** (4.2 g, 85%), mp 214–217 °C.

Anal. Calcd for $C_{20}H_{24}N_2O_6$: 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-LICAMS, 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 H_2SO_4 (45 mL). Workup and recrystallization from H_2O gave **13**·$2H_2O$ (3.2 g, 48%): mp 253–254 °C dec; IR 2500–3700 (>CH, -OH), 1640 (-CON<), 1590, 1550, 1425, 1280, 1215 (SO_3^-), 1165 (SO_3^-), 1105, 1040, 610 (SO_3^-) cm^{-1}; NMR δ 1.2–1.9 [broad, 8 H, $-(CH_2)_4CH_2NH-$], 3.2–3.6 [broad, 4 H, $-(CH_2)_4CH_2NH-$], 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 $C_{20}H_{24}N_2O_{12}S_2$·$2H_2O$: 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)-1,5,9,13-tetraazacyclohexadecane 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 H_2SO_4 (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 H_2O/MeOH. (A portion of this filtrant gave no blue color in the presence of aqueous $FeCl_3$.) The combined filtrate and wash was evaporated to dryness and then redissolved in minimum H_2O. Careful addition of MeOH, then EtOH, and finally Et_2O (to give substantial turbidity) followed by filtration gave a clear, nearly colorless solution. Subsequent addition of 2–3 volumes of Et_2O 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**·$5H_2O$ (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, $-CH_2CH_2N<$), 2.8–4.2 (broad, 16 H, $-CH_2N<$), 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 $C_{40}H_{40}N_4O_{24}Na_4$·$5H_2O$: 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)-1,6,11,16-tetrahexadecane 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); NEt_3 (3.54 g, 35 mmol); DMAA (40 mL). The reaction mixture was evaporated to residual oil which was partitioned between H_2O/$CHCl_3$. Next the $CHCl_3$ layer was washed well with aqueous HCl, H_2O, then aqueous NaOH before drying with $MgSO_4$ and elution from an alumina column with mixtures of 0–5% EtOH in CH_2Cl_2. 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 (>N*CO*-) cm^{-1}. This material was used in the next step.

Anal. Calcd for $C_{48}H_{62}N_4O_{12}$: 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); BBr_3 (4 mL, 42 mmol); CH_2Cl_2 (115 mL). After hydrolysis with H_2O (50 mL), the crude product was collected by filtration and washed well with H_2O to remove acids, then with Et_2O, and dried in a vacuum desiccator over P_2O_5/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**·$4H_2O$·$1/4Na_2SO_4$ (1.4 g, 88%): IR 2800–3700, 1600 (>NCO–), 1475, 1150–1300 (SO_3^-), 1100, 1045, 620 (SO_3^-) cm^{-1}; NMR δ 1.3–2.1 (broad, 12 H, $-CH_2CH_2CH_2N<$), 2.8–3.8 (broad, 12 H, $-CH_2N<$), 7.2–8.0 (complex m, 8 H, ArH). pH titration gave pK_{a_1} = 7.49 (4 protons), pK_{a_2} = 12.10 (4 protons), for four catechol units.

Anal. Calcd for $C_{40}H_{42}N_4O_{24}S_4Na_4$·$4H_2O$·$1/4Na_2SO_4$: 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); NEt_3 (4.05 g, 40 mmol); DMAA (40 mL). Evaporation of the reaction mixture gave

an oily residue which was partitioned between H_2O/CH_2Cl_2. Purification of this crude product in CH_2Cl_2 solution was accomplished as in the synthesis of **16.** In this way a 4-g fraction of the tetra(2,3-dimethoxybenzoyl) 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); BBr_3 (4.2 mL, 44 mmol); CH_2Cl_2 (115 mL). Hydrolysis (50 mL, H_2O), filtration, and thorough water wash, then vacuum drying at room temperature over P_2O_5/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 H_2SO_4 (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**·6.5H_2O (2.1 g, 50%) was obtained: IR 3700–2500 (>CH, -OH), 1640–1590 (-CON<), 1470, 1420, 1380, 1210–1180 (SO_3^-), 1100, 1040, 615 (SO_3^-) cm^{-1}; NMR δ 1.3–2.3 (broad, 8 H, $-CH_2CH_2N<$), 2.8–3.8 (broad, 12 H, $-CH_2N<$), 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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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 $\{[Fe(\eta^5\text{-}C_5H_5)(\eta^5\text{-}C_5H_4)]_2Se\}I_3 \cdot I_2 \cdot {}^1/_2CH_2Cl_2$ 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, α = 97.65 (4)°, β = 95.73 (4)°, γ = 88.10 (4)°, and V = 1406.5 Å^3. 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 Kα) to give conventional discrepancy factors of R = 0.0616 and R_w = 0.0654. Discrete mixed-valence $[Fe(\eta^5\text{-}C_5H_5)(\eta^5\text{-}C_5H_4)]_2Se^+$ 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 $Fe(\eta^5\text{-}C_5H_5)(\eta^5\text{-}C_5H_4)$ moieties are structurally different. One is a ferrocenyl group, the other a ferricenyl group. The localized nature of the mixed-valence cation is substantiated by ^{57}Fe 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 low-energy 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 ^{57}Fe 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-

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