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Synthesis of Dinuclear Boron Complexes of Sulfinylcalix[4]arenes: Syn/Anti Stereocontrol by the Arrangement of the Sulfinyl Functions

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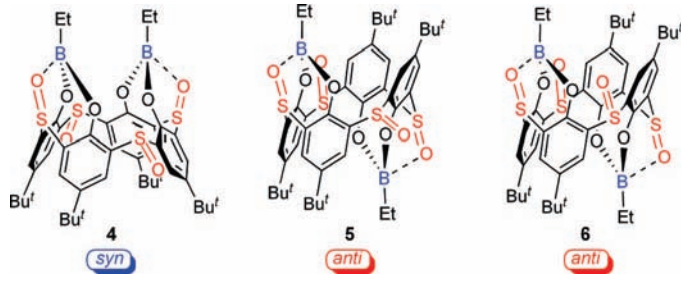
ABSTRACT



Stereocontrol in the synthesis of dinuclear metal complexes of sulfinylcalix[4]arenes 2 has been achieved by the arrangement of sulfinyl functionalities. Thus, the treatment of the *rtct* isomer of 2 (2_{rtct}) with an excess of Et_3B affords syn dinuclear boron complex 4, while a similar treatment of *rctt* and *rcct* isomers 2_{rctt} and 2_{rcct} yields anti dinuclear complexes 5 and 6, respectively.

The development of multinuclear metal complexes has been the subject of intense research activity because they often exhibit unique properties that cannot be displayed by mononuclear complexes.[1] Therefore, there has been considerable interest in the design and synthesis of multidentate ligands that can regioselectively and stereoselectively accommodate more than two metal ions.[2] In this context, *p-tert*-butylthiacalix[4]arene (**1**) and its oxidized derivatives, namely, *p-tert*-butylsulfinyl- (**2**) and *p-tert*-butylsulfonylcalix[4]arene (**3**),[3] are promising because they possess heterotopic coordination sites. This means that sulfur and/or oxygen atoms of the bridging moieties and the phenolic hydroxy groups together exhibit unique binding properties toward soft and/or hard metal ions to form multinuclear or supramolecular metal complexes.[4] We have recently reported that compound **1** on treatment with $TiCl_4$ affords two dinuclear titanium complexes, in which **1** ligates to each titanium ion in a tridentate fashion through an epithio linkage and the two

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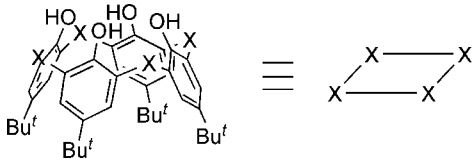
neighboring phenoxy oxygen atoms; the calixarene ligand adopts a cone or 1,2-alternate conformation in each complex, forcing the two metal centers to occupy syn or anti positions with respect to the mean plane defined by the macrocycle.[5] The syn complex exhibited high catalytic activity in the Mukaiyama aldol reaction of aromatic aldehydes with silyl enol ethers, indicating the double-activation ability of the complex as a bidentate Lewis acid toward aldehydes.[5a] On the other hand, the anti complex was found to be an efficient catalyst for the cyclotrimerization of terminal alkynes with high stereoselectivity toward 1,3,5-trisubstituted benzenes over 1,2,4-trisubstituted isomers.[5b] Therefore, the development of multinuclear metal complexes of calixarenes is highly desirable. However, it is generally difficult to prepare a specific complex by the treatment of a calix-type ligand with metal salt(s). Moreover, it is often the case that one cannot even predict how many and what kind of complexes will be formed in such a reaction.[6]



1: X = S
2: X = SO
3: X = SO_2

Sulfinylcalix[4]arene **2** has four stereoisomers (*rtct*, *rctt*, *rcct*, and *rccc*) originating from the arrangement of the four sulfinyl functions (Figure 1). Recently, we have succeeded

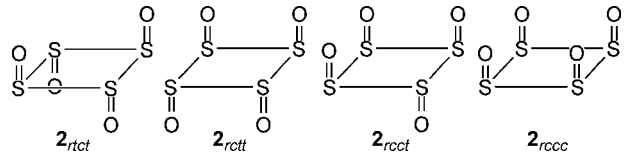
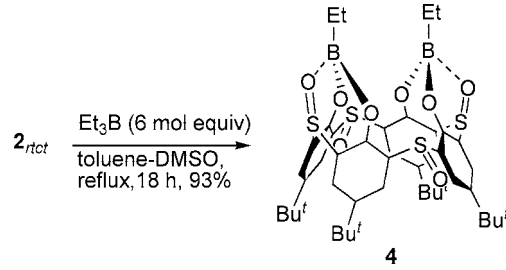


Figure 1. Schematic views of stereoisomers of compound **2**. The dispositions of the sulfinyl oxygen atoms are denoted by the term cis (*c*) or trans (*t*) that is relative to the reference sulfinyl oxygen atom (*r*) with respect to the mean plane defined by the four sulfur atoms as suggested by Böhmer.[3a] The notation proceeds around the system in a direction from the reference oxygen, which is chosen in order to prioritize cis over trans and maximize the number of cis.

in preparing all of the stereoisomers by the direct oxidation of **1** or by the stereocontrolled oxidation of its tetra-*O*-benzyl derivatives and subsequent debenzylation.[7] We reasoned that the direction of the sulfinyl moieties should be utilized for controlling the stereostructures of their multinuclear metal complexes, by considering the characteristics of soft S and hard O atoms, if metal ions are properly chosen.[8] In the first successful application of this strategy, in this study, we report the stereoselective synthesis of dinuclear boron complexes of sulfinylcalixarenes **2**.

First, the reaction of *rtct* isomer $\mathbf{2}_{rtct}$ with Et_3B was examined. The treatment of $\mathbf{2}_{rtct}$ with an excess of Et_3B (6 mol equiv) in toluene−DMSO (3:1) at 110 °C for 18 h afforded complex **4** in 93% yield after the recrystallization from dichloromethane−hexane (Scheme 1). The complex

Scheme 1. Synthesis of Complex **4**[a]



[a]The aromatic rings are depicted as hexagons for clarity.

exhibited a parent ion peak at 861 [$(M + 1)^+$] in the fast atom bombardment (FAB) mass spectrum, suggesting that it is a bis(ethylboronate) complex formulated as $[B_2L(C_2H_5)_2]$ ($H_4L = \mathbf{2}_{rtct}$). The ^1H NMR spectrum exhibited one singlet for the *tert*-butyl protons (36H) and two doublets for the aryl protons (4H each) (Figure 2a); the magnetic equivalences

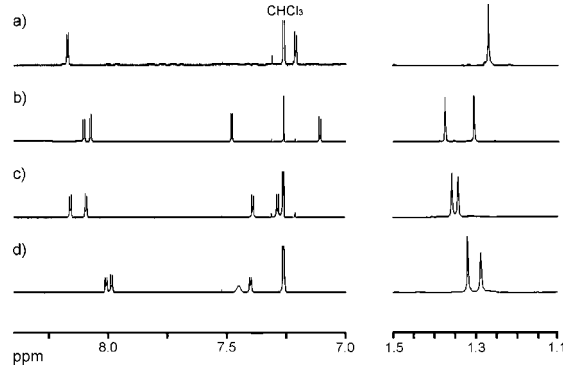


Figure 2. Partial ^1H NMR spectra of boron complexes in $CDCl_3$ (400 MHz): (a) **4**, (b) **5**, (c) **6**, and (d) **7**.

suggested a C_{2v}-symmetric structure, that is, cone conformation with the syn arrangement of the two boronate moieties. Further, a more detailed structure of complex **4** was revealed

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(6) A few examples for the stereoselective synthesis of dinuclear metal complexes of **1** have been reported: (a) Takemoto, S.; Tanaka, S.; Mizobe, Y.; Hidai, M. *Chem Commun.* **2004**, 838. (b) Zeller, J.; Treptow, J.; Radius, U. *Z. Anorg. Allg. Chem.* **2007**, *633*, 741.

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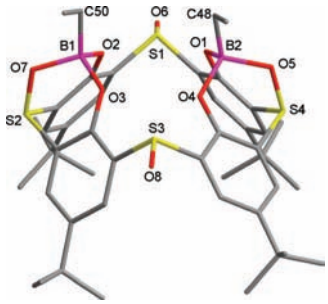


Figure 3. X-ray structure of complex **4**. Protons and solvents are omitted for clarity. Selected bond distances (Å): B1−O2 1.4837(43), B1−O3 1.4705(43), B1−O7 1.5601(44), B1−C50 1.5730(48), B2−O1 1.4665(39), B2−O4 1.4908(38), B2−O5 1.5489(40), B2−C48 1.5769(45), S1−O6 1.4933(23), S2−O7 1.5611(24), S3−O8 1.4978(21), S4−O5 1.5653(21).

by the X-ray crystallographic analysis (Figure 3). As expected, it was a syn bis(ethylboronate) complex with a cone conformation. The calix ligand coordinates to each boron ion in a tridentate fashion through a sulfinyl oxygen atom and the two adjacent phenoxy oxygen atoms. The complete syn selectivity can be understood on the basis of the coordination of the sulfinyl groups to hard boron ions not with the soft S atoms but exclusively with the hard O atoms. Interestingly, S═O bonds were slightly elongated by the coordination; the bond lengths of the coordinating sulfinyl groups were 1.5611(24) and 1.5653(21) Å, respectively, while those of the other sulfinyl groups were 1.4933(23) and 1.4978(21) Å.

The reaction of *rctt* isomer $\mathbf{2}_{rctt}$ with Et_3B that was conducted in refluxing toluene required a large excess of the boron reagent (20 molar equiv) and a prolonged reaction time (4 days). Although the ^{1}H NMR analysis of the resulting reaction mixture revealed the almost exclusive formation of complex **5** (Figure 4), the recrystallization of the crude compound from dichloromethane−hexane afforded moderate yield (45%), which was attributed to the decomposition during the purification. The FAB mass spectrum of the compound exhibited a parent ion peak at 861, which is attributed to the protonated molecular ion peak of a bis(ethylboronate) complex. On the other hand, the ^{1}H NMR spectrum exhibited a quartet (4H) and triplet (6H) for the ethyl protons, two singlets for the *tert*-butyl protons (18H each), and four doublets for the aryl protons (2H each) (Figure 2b), suggesting that the complex has a symmetric structure with an inversion center. Therefore, the calix ligand should adopt a 1,2-alternate conformation. This assignment was supported by the chemical shift values of the ethyl signals [δ −0.20 (4H, quartet) and 0.05 (6H, triplet)], which appeared considerably upfield as compared to those of complex **4** [δ 0.94−0.99 (10H, multiplet)], indicating the anisotropic shielding effects of the facing benzene rings. These observations, combined with the fact that the sulfinyl groups of $\mathbf{2}_{rtct}$ bound to boron ions exclusively with the oxygen atoms to form complex **4** (vide supra), allowed us

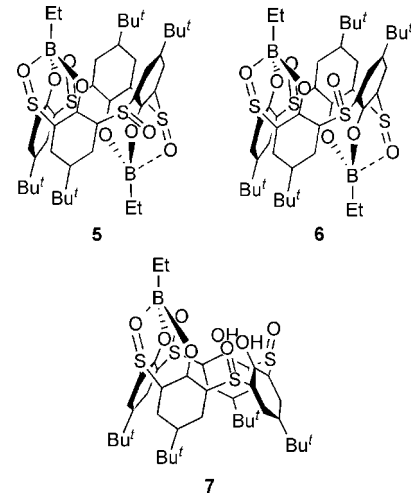


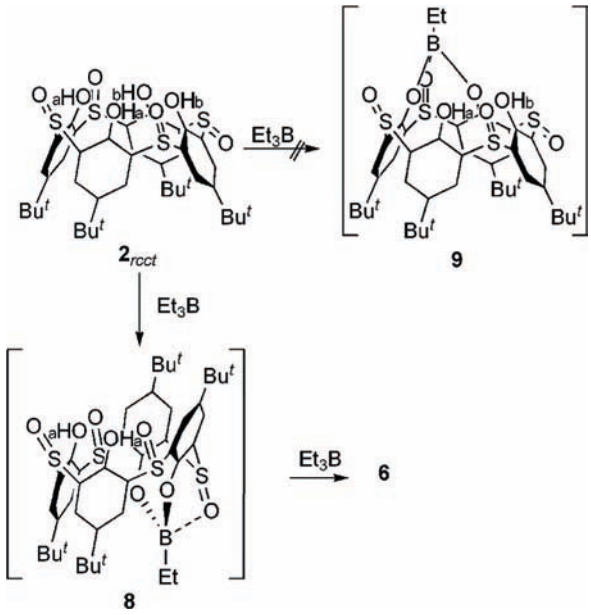
Figure 4. Schematic views of complexes **5**−**7**. The aromatic rings are depicted as hexagons for clarity. The conformation of the calix ligand $\mathbf{2}_{rccc}$ in complex **7** is uncertain.

to assign the structure depicted in Figure 4 to complex **5**.[9] Thus, the stereoselective construction of syn (**4**)/anti (**5**) dinuclear metal complexes of sulfinylcalixarenes **2** has been achieved by the disposition of the sulfinyl moieties.

Considering the fact that the sulfinyl moieties of the above-mentioned two stereoisomers ligated to boron ions selectively with the oxygen atoms, *rcct* isomer $\mathbf{2}_{rcct}$, in which a couple of facing sulfinyl groups are oriented cis and the others are oriented trans to each other, is likely to form both syn and anti dinuclear boron complexes. However, the treatment of $\mathbf{2}_{rcct}$ with an excess of Et_3B (8 molar equiv) in refluxing toluene for 24 h resulted in the exclusive formation of complex **6** (Figure 4). The FAB mass spectrum of the compound exhibited a parent ion peak at 861, indicating that it is a bis(ethylboronate) complex. On the other hand, the ^{1}H NMR spectrum exhibited two triplets (3H each) and two quartets (2H each) for the ethyl protons and two singlets (18H each) for the *tert*-butyl protons and four doublets (2H each) for the aryl protons (Figure 2c); the magnetic equivalences suggested a C_s-symmetric structure in which the facing sulfinyl groups of the trans conformation are in the σ-plane. In addition, the unequivalent resonance of the two ethyl protons indicated that the trans sulfinyl groups bind to the boron atoms to form a complex with the 1,2-alternate conformation (Figure 4); if the cis sulfinyl groups bound to boron atoms in a similar manner, the two ethyl moieties, which were out of the σ-plane, should be equivalent. This was supported by the upfield shifts of the ethyl protons [δ −1.18 and −0.07 (3H each, quartet) and 0.50 and 0.70 (2H each, triplet)] that were attributed to the anisotropic shielding effects due to the facing benzene rings, which is similar to the case of compound **5** (vide supra). The selective formation of the anti dinuclear complex can be understood by the reaction mechanisms depicted in Scheme 2. There are two

(9) X-ray crystallography of complex **5** revealed that it adopted a 1,2-alternate conformation but the *R* value could not be improved.

Scheme 2. Mechanisms for the Stereoselective Formation of Anti Complex **6**[a]



[a]The aromatic rings are depicted as hexagons for clarity. The conformation of the calix ligand $\mathbf{2}_{rcct}$ in complex **8**, as well as that of $\mathbf{2}_{rcct}$ itself, is uncertain.

kinds of hydroxy groups, OH_a and OH_b, in $\mathbf{2}_{rcct}$; OH_a is placed between two adjacent sulfinyl groups of the cis conformation while OH_b is placed between those of the trans conformation (Scheme 2). It is easily conceivable that the acidity of OH_b is higher than that of OH_a because the former hydroxy group forms only one hydrogen bond with either of the two adjacent sulfinyl groups at a time, while the latter can form two hydrogen bonds simultaneously with the two adjacent sulfinyl groups. Therefore, the two OH_b groups that are more acidic, and therefore, more reactive, first bind to Et_3B with the assistance of the sulfinyl oxygen located between the two OH_b groups to form mononuclear complex **8**. This complex subsequently ligates to another molecule of the boron reagent by the two OH_a groups and the interpositioned sulfinyl oxygen to afford the anti dinuclear complex **6**.

Contrary to the abovementioned three isomers, *rccc* isomer $\mathbf{2}_{rccc}$, on being treated with a large excess of Et_3B (40 molar equiv) in refluxing toluene, yielded only mononuclear boron complex **7** in 90% yield (Figure 4), even after a prolonged reaction time (3 days). The identity of the product was confirmed by the FAB mass [823 $(M + 1)^+$] and ^1H NMR spectra, which exhibited a triplet (3H) and quartet (2H) for the ethyl protons, two singlets (18H each) for the *tert*-butyl protons, and four doublets (2H each) for the aryl protons (Figure 2d). The low reactivity of $\mathbf{2}_{rccc}$ is attributed to the weak acidity of the four hydroxy groups located between two adjacent sulfinyl groups of cis conformation to form strong intramolecular hydrogen bonds. This observation agrees well with the reaction mechanisms for the stereoselective formation of complex **6** (vide supra).

In conclusion, in this paper, we proposed a convenient method for the stereoselective synthesis of dinuclear boron complexes of sulfinylcalix[4]arenes **2**. The selective coordination of the hard sulfinyl oxygen atom of **2** toward a hard boron ion in cooperation with the two neighboring hydroxy groups, as well as the preferential ligation of the hydroxy group located between two sulfinyl groups of trans conformation, arranged two boron ions in syn and anti relationships with respect to the mean plane defined by the four sulfur atoms. The stereoselective synthesis of other metal complexes of **2** is currently under investigation.

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Supporting Information Available: Experimental procedures and characterization data for complexes **4**−**7**. X-ray structure for complex **4** (CIF). This material is available free of charge via the Internet at http://pubs.acs.org.

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