Table II. Synthesis of Alkyldibromoborane-Methyl Sulfide Addition Compounds and Their Derivatives by the Hydroboration of Olefins with Dibromoborane-Methyl Sulfide, $HBBr_2{\cdot}SMe_2$, in Refluxing Methylene Chloride

Alkyldibromoborane derivative	Isolated yield, %	Bp, °C (mm)
n-Hexyldibromoborane-methyl sulfide	91	97-100 (1)
3-Hexyldibromoborane-methyl sulfide	90	73-75 (2.2)
2-Methyl-1-pentyldibromoborane-methyl sulfide	93	82-85 (1.6)
Cyclopentyldibromoborane-methyl sulfide[a]	93	140-144 (2.1)
trans-2-Methylcyclohexyldibromoborane-methyl sulfide[b]	86	68-69 (0.5)
n-Hexyldibromoborane	71	56-58 (0.9)
Dimethyl *n*-hexylboronate	83	84-86 (35)

[a] Solid at 25 °C, contained 18% of the uncomplexed compound. [b] Contained 19% of the uncomplexed compound.

Dibromoborane was prepared by a slow, dropwise addition of 80.2 mL (212 g, 846 mmol) of BBr_3 to a mixture of 40.0 mL (423 mmol) of $H_3B{\cdot}SMe_2$ and 62.1 mL (52.6 g, 846 mmol) of methyl sulfide at 0 °C, followed by stirring at 40 °C for 12 h. Under these conditions, the redistribution is essentially complete (eq 6).

$$H_3B{\cdot}SMe_2 + 2SMe_2 + 2BBr_3 \rightarrow 3HBBr_2{\cdot}SMe_2 \quad (6)$$

The resulting colorless, viscous liquid (at 40 °C) was characterized by spectroscopic methods.[8] It was 7.8 M in active hydride. No other boron species were detected in significant amounts by ^{11}B NMR. Therefore, the material is 7.8 M in the desired reagent, $HBBr_2{\cdot}SMe_2$.

1-Hexene, 100 mmol (12.5 mL), was dissolved in 75 mL of CH_2Cl_2 in a flask fitted with a reflux condenser and maintained under nitrogen. To this flask was added 100 mmol (12.8 mL) of $HBBr_2{\cdot}SMe_2$ and the reaction mixture was heated under reflux for 3 h. After the mixture cooled to 25 °C, the solvent was removed using a water aspirator. The product, distilled at 97-100 °C (1 mm), was obtained in a yield of 29 g, 91%. Examination of the ^1H NMR spectrum revealed a CH_3 signal at δ 2.45, characteristic of the $RBBr_2{\cdot}SMe_2$ derivatives.

The following procedure was used to prepare free *n*-hexyldibromoborane. Following completion of the hydroboration stage the reaction mixture was brought to 0 °C and 105 mmol (10.0 mL) of BBr_3 was added. The reaction mixture was stirred at 25 °C for 1 h. Solvent was removed with the aid of a water aspirator. A white solid, $Br_3B{\cdot}SMe_2$, separated. Distillation gave 18.0 g (71%) of *n*-hexyldibromoborane, bp 56-58 °C (0.9 mm). (The bath temperature was maintained below 100 °C to avoid melting of $Br_3B{\cdot}SMe_2$, mp 108 °C.)

To obtain the dimethyl boronate, the hydroboration reaction mixture was cooled to 0 °C and treated with 200 mmol of CH_3ONa in methanol (4.5 M). After 2 h at 25 °C, the solvent was removed and the product distilled (without separating the precipitated sodium bromide) to obtain 13.1 g (83%) of dimethyl *n*-hexylboronate,[2] bp 84-86 °C (35 mm).

As mentioned earlier, this ability of $HBBr_2{\cdot}SMe_2$ to hydroborate alkenes directly was unexpected. The reactivities of the borane etherates and borane-methyl sulfides decrease in the order $H_3B{\cdot}OR_2 > H_2BCl{\cdot}OR_2 > HBCl_2{\cdot}OR_2$, and $H_3B{\cdot}SMe_2 > H_2BCl{\cdot}SMe_2 > HBCl_2{\cdot}SMe_2$. This was attributed to the increase in the Lewis acidity of the borane component with the number of chlorine substituents: $H_3B < H_2BCl < HBCl_2 < BCl_3$.[8] It was believed that the reaction proceeds via a prior dissociation of the addition compound. The stabler the complex, the smaller the amount of free borane, and the slower the hydroboration.

It is known that BBr_3 is a stronger Lewis acid than BCl_3, attributed to decreased resonance contributions of the boron-bromine bond.[4] According to the above interpretation, the bromoboranes should be more acidic than the corresponding chloroboranes: $BBr_3 > BCl_3$; $HBBr_2 > HBCl_2$; $H_2BBr > H_2BCl$. Since $HBCl_2{\cdot}SMe_2$ fails to react with olefins at a convenient rate, $HBBr_2{\cdot}SMe_2$ was expected to be even less reactive.

Some support for this prediction was obtained by ^1H NMR observations.[8] In CCl_4 solution, $Cl_3B{\cdot}SMe_2$ readily exchanges with excess SMe_2. On the other hand, such exchange was not observed for $Br_3B{\cdot}SMe_2$. This was attributed to the greater stability of the bromine derivative. Similarly, $HBCl_2{\cdot}SMe_2$, undergoes such exchange, whereas $HBBr_2{\cdot}SMe_2$ does not, apparently confirming the greater stability of the latter.[8]

There is evidence that π electrons, such as those in benzene, can interact strongly with the $Br_3B{\cdot}SMe_2$ addition compound.[8,9] Possibly, a similar phenomenon occurs involving the π electrons of the alkene and the dibromoborane adduct, $HBBr_2{\cdot}SMe_2$. If so, the hydroboration may involve a direct transfer of the $HBBr_2$ moiety from sulfur to the π electrons.

Irrespective of the final theoretical interpretation of this fascinating new development, it has important synthetic implications. It provides a new stable monofunctional hydroborating agent which can be used in the absence of added Lewis acids. It makes available a convenient synthetic route to the alkyldibromoboranes, not previously available. It makes possible, for the first time, the systematic exploration of their chemistry. Finally, it opens up a more convenient route to the alkylboronic acids and esters and to the many synthetic applications for which they can be utilized.

References and Notes

(1) H. C. Brown and N. Ravindran, *J. Am. Chem. Soc.*, **98**, 1785 (1976).
(2) H. C. Brown and N. Ravindran, *J. Org. Chem.*, **42**, 2533 (1977).
(3) H. C. Brown and N. Ravindran, *J. Am. Chem Soc.*, **98**, 1798 (1976).
(4) H. C. Brown and R. R. Holmes, *J. Am. Chem. Soc.*, **78**, 2173 (1956).
(5) M. J. Bula and J. S. Hartman, *J. Chem. Soc., Dalton Trans.*, 1047 (1973).
(6) H. C. Brown and N. Ravindran, *Synthesis*, in press.
(7) H. C. Brown and G. Zweifel, *J. Am. Chem. Soc.*, **82**, 4708 (1960).
(8) H. C. Brown and N. Ravindran, *Inorg. Chem.*, in press.
(9) See Figure 1 in ref 8.
(10) Postdoctoral research associate on NSF Grant No. GP 6942X and 41169X.

Herbert C. Brown,* N. Ravindran[10]
Richard B. Wetherill Laboratory, Purdue University
West Lafayette, Indiana 47907

Received July 15, 1977

Mechanism of Nickel(0)-Catalyzed Dimerization of 1,3-Butadiene

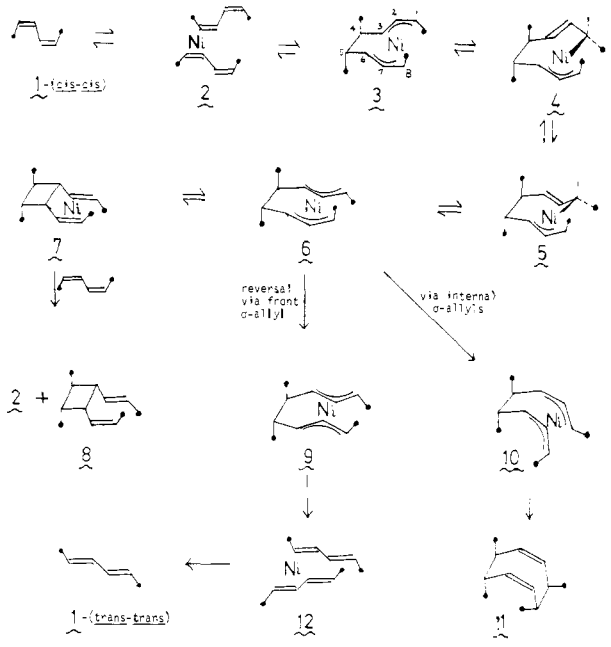
Sir:

We wish to report details of the mechanism of the nickel-catalyzed dimerization of butadiene. Our results, taken together with the pioneering efforts of Wilke,[1] Heimbach,[2] and co-workers, allow a complete picture to be proposed for this intriguing transformation.

For the formation of divinylcyclobutane from butadiene we propose a series of complex, but well-precedented, steps. This mechanism, an expansion of an earlier suggestion of Mango[3] and Heimbach and Traunmüller,[4] is shown in Scheme I. The proposal has as key steps preferential formation of *anti*-π-allyl[5] complex[6] **3**, and transformation of **3** via σ-allyls[1c,7] **4** and **5** to *syn*-π-allyl **6**. This latter species is clearly well disposed for the reductive elimination to yield *cis*-divinycyclobutane (**8**) via **7**.

Examination of the mechanism in detail makes it clear that

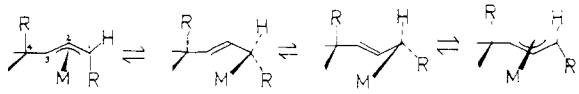
Scheme I. Formal Mechanism[9] for the $Ni(COD)_2$-Catalyzed Dimerization of a 1,4-Disubstituted Diene. Added Phosphine Ligand, Required for This Reaction, Is Not Shown



the use of a disubstituted diene would reveal most of the important stereochemical features of this system. In this paper we direct particular attention to two aspects: the stereochemistry of the divinylcyclobutane where extensive, but stereospecific, epimerization of the labeling is anticipated, and the structure of recovered diene, also expected to be isomerized (again stereospecifically) since the overall reaction is known to be reversible. *cis,cis*-1,4-Dideuterio-1,3-butadiene (*cis,cis*-**1**), a substrate used previously by us,[8] proved to be ideal for this purpose, reacting smoothly to produce dimers under Wilke conditions[1] (benzene solvent, bis(1,5-cyclooctadiene)-nickel(0) catalyst, triphenylphosphine, room temperature, N_2 atmosphere).

Examination of recovered diene in this reaction revealed a rapid *double* isomerization of *cis,cis*-**1** to *trans,trans*-**1**. Even at reaction times where cis,cis has been >40% converted to trans,trans, no cis,trans diene isomer could be detected under conditions which would have revealed 1–2%. This novel isomerization is most easily explained by an allyl isomerization proceeding via σ complexes. As shown in Scheme II, such an allyl isomerization would invert the original stereochemical relationships of both R groups with respect to the allyl.

Scheme II. Allyl Isomerization Mechanism



In our mechanism, Scheme I, reversal of **6** to **1** via the *same* σ-allyls employed in the forward reaction results in no isomerization of *cis,cis*-**1**. Reversal via the other possible terminal σ-allyl, however, results in the formation of **9** and then **12** and *trans,trans*-**1**, where *both diene units have been isomerized at both termini*. Other possible scrambling mechanisms do not permit this coupled double isomerization. In particular, complete dissociation of the allyl, followed by rotation about C_3 and C_4, would eventually produce cis,trans diene **1** (not observed). Internal σ-allyls, i.e., formation of the C_3Ni σ species, cannot isomerize the diene, but may lead to different products, especially cyclooctadiene, vide infra.

Examination of the deuterium stereochemistry in the divinylcyclobutane is equally instructive. Again reference to Scheme I suggests that a highly stereospecific result should prevail. Despite the possibility of equilibria **6** ⇌ **2** or **6** ⇌ **12**, dimer **8** will always be formed with one vinyl group of cis configuration, with one trans, and with a trans disposition of the 3,4 deuteriums in the ring. Demonstration of this stereochemical relationship could be easily accomplished by Cope rearrangement[10] of **8** to 1,5-cyclooctadiene in which 3,4 and 7,8 deuteriums should be trans. Oxidation of this cyclooctadiene to succinic acid provides for a simple analysis since *dl*- and *meso*-3,4-dideuteriosuccinic anhydrides are easily distinguishable.[11,12]

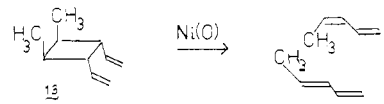
Unfortunately, the rapid isomerization of starting material *cis,cis*-**1** ⇌ *trans,trans*-**1** makes it impossible to obtain a clean result in this experiment since crossed cycloaddition of cis,cis with trans,trans will lead to precisely the opposite result (i.e., ultimately *meso*-succinic anhydride-d_2).

At the lowest possible conversion of diene to product **8** (5%), diene *cis,cis*-**1** had isomerized to *trans,trans*-**1** to the extent of 33%. Cope rearrangement of VPC-purified **8** followed by conversion to succinic anhydride revealed 30 ± 2% *meso*- and 70 ± 2% *dl*-succinic anhydride-d_2. Closed form solution of the kinetic expression for this system suggests that one would expect in fact exactly 30% of the cycloadditions to occur between *cis,cis*-**1** and *trans,trans*-**1** for a system whose final composition is 33% *trans,trans*-**1** as found.[13]

At higher conversions to product, higher meso content is found in the resulting succinic anhydride. Thus at a conversion to dimer of ~10%, *trans,trans*-**1** had nearly reached its equilibrium content of 50% and *meso*-succinic anhydride-d_2 constituted 40% of the meso-*dl* mixture. These results strongly suggest that, at hypothetical 0% conversion, all of the succinic anhydride will be *dl*, implying the stereochemistry of structure **8** as shown.[14]

This result is equally in support of the mechanism in that it obviously requires a formulation of the initial complexes **2** and **3** as anti, and provides additional supporting evidence for the involvement of σ-allyls **4** and **5**.

These results are also consistent with the earlier work of Heimbach and Hey,[2a] shown in part below. Our mechanism provides a sound explanation for the single isomerization noted by these workers in the conversion of **13** to equal parts of *cis*- and *trans*-piperylene.



Cyclooctadiene-d_4 (**11**) is also a product of this reaction. Analysis of this product from the same low conversion run (by oxidation to succinic acid-d_2) reveals the same result, 31 ± 3% *meso*- and 69 ± 3% *dl*-succinic anhydride-d_2. This result is most easily accommodated by again employing **6** as a key intermediate. *syn*-σ-Allyl **6** can isomerize to *syn*-π-allyl **10** by a series of *internal* σ-allyls. Complex **10** is ideally disposed toward reductive elimination to yield cyclooctadiene. Since no further net scrambling of deuterium stereochemistry occurs in the conversion of **6** to **10**, this cyclooctadiene should have a structure identical with that derived from thermal Cope rearrangement of **8**. Our results are again in close agreement with this expectation.

Acknowledgment is made to the donors of the Petroleum Research Fund, administered by the American Chemical Society, for support of this work.

References and Notes

(1) (a) W. Brenner, P. Heimbach, H. Hey, E. W. Müller, and G. Wilke, *Justus Liebigs Ann. Chem.*, **727**, 161 (1969); (b) P. W. Jolly, I. Tkatchenko, and G. Wilke, *Angew. Chem., Int. Ed., Eng.*, **10**, 328, 329 (1971); (c) B. Barnett, B. Büssmeier, P. Heimbach, P. W. Jolly, C. Krüger, I. Tkatchenko, and G.

Wilke, *Tetrahedron Lett.*, 1457 (1972); (d) for an early review, see G. Wilke, *Angew. Chem., Int. Ed. Engl.*, **2**, 105 (1963).
(2) (a) P. Heimbach and H. Hey, *Angew. Chem., Int. Ed. Engl.*, **9**, 528 (1970); (b) P. Heimbach and W. Brenner, *ibid.*, **6**, 800 (1967); (c) for reviews, see H. Buchholz, P. Heimbach, H. Hey, H. Selbeck, and W. Wiese, *Coord. Chem. Rev.*, **8**, 129 (1972); and P. Heimbach, *Angew. Chem., Int. Ed. Engl.*, **12**, 975 (1973).
(3) F. D. Mango, *Coord. Chem. Rev.*, **15**, 109 (1975).
(4) P. Heimbach and R. Traunmüller, "Chemie der Metall-Olefin Komplexe", Verlag Chemie, Weinheim/Bergstr., Germany, 1970.
(5) In this discussion we shall use anti and syn to describe the *relative* disposition of the two allyl units in these bis allyl complexes. To avoid confusion we shall use cis and trans to describe the geometry of an individual allyl unit.
(6) For representative allyl structures, see R. Uttech and H. Dietrich, *Z. Kristallogr., Kristallgeom., Kristallphys., Kristallchem.*, **122**, 60 (1965).
(7) G. E. Coates, M. L. H. Green, and K. Wade, "Organometallic Compounds. Volume Two, The Transition Elements", Methuen, London, 1968, p 39.
(8) (a) L. M. Stephenson, R. V. Gemmer, and J. I. Brauman, *J. Am. Chem. Soc.*, **94**, 8620 (1972); (b) L. M. Stephenson, R. V. Gemmer, and S. Current, *ibid.*, **97**, 5909 (1975).
(9) For convenience we have shown all of the species (except **10** and **11**) with a trans geometry about the C_2–C_3 and C_6–C_7 bonds. Obviously, formation of an internal σ-allyl (i.e., to C_3 or C_6) could lead, via C_2–C_3 or C_6–C_7 rotation, to cis species which may be sterically more favorable in some cases. In fact, x-ray and NMR data[1c] indicate that a cis–trans formulation is probably the energy minimum in this bis allyl family. None of these internal σ-allyls, or the rotations that result from them, can alter the deuterium stereochemistry. This is illustrated in the conversion of **6** to 1,5-cyclooctadiene (**11**), via the bis cis species **10**. Note that this same species could serve as a precursor to *cis*-divinylcyclobutane (**8**) with unchanged deuterium stereochemistry.
(10) G. S. Hammond and C. D. DeBoer, *J. Am. Chem. Soc.*, **86**, 899 (1964).
(11) This analysis is accomplished[12] by Raman spectroscopy, using a Spex 14018 Raman spectometer equipped with a Spectra-Physics Argon ion laser (4880-Å excitation line). The meso anhydride shows bands at 691 and 1058 cm^{-1}, whereas the *dl* appears at 723 and 1100 cm^{-1}.
(12) For earlier methods of this analysis, see C. R. Childs, Jr., and K. Block, *J. Org. Chem.*, **26**, 1630 (1961).
(13) An approximation of this number can be obtained by recognizing that the average composition of the system is $\sim 33\% \div 2 = 16.5\%$ trans,trans. Thus the number of crossed cycloadditions should be in the range of $2(0.165 \times 0.835) = 28\%$.
(14) Our analysis will only distinguish the relative stereochemistry of adjacent (3,4 or 7,8) deuteriums in the cyclooctadiene. Our drawings imply that the mutual relationship of 3,7 and 4,8 deuteriums is syn, as a Cope rearrangement of **8** would require. No presently conceivable mechanism which would allow this relationship to be anti is consistent with the interconversion *cis,cis*-**1** ⇌ *trans,trans*-**1**. Methods which would establish this more remote interrelationship of deuteriums are under investigation.
(15) Alfred P. Sloan Foundation Fellow.

Charles R. Graham, L. M. Stephenson*[15]
Department of Chemistry
Case Western Reserve University
Cleveland, Ohio 44106
Received June 27, 1977

Cyclodextrin Flexibly Capped with Metal Ion[1]

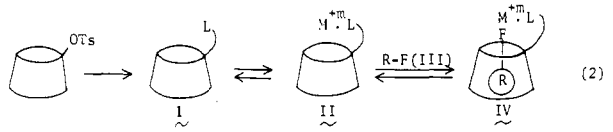
Sir:

Highly specific binding of substrates by hydrophobic sites of enzymes in *water* is satisfactorily modelled by artificial hosts such as parent[2] or modified[3] cyclodextrins or cyclophanes.[4] Thus, introduction of a metal ion into functionalized cyclodextrin may be an appropriate model for the studies of binding by metalloenzymes. Breslow et al.[5] reported a beautiful example of an "artificial metalloenzyme" in which a metal ion acts as a *joint* to bind the hydrophobic cavity (binding site) and the oxymate anion (catalytic site), where a substrate is bound by *single recognition* as shown by b in eq 1 as far as binding characteristics are concerned[6] (CD, cyclodextrin; M^{m+}, metal

$$\mathrm{CD{-}L} + \mathrm{M}^{m+} + \mathrm{F} \rightleftharpoons \underset{\text{a}}{\mathrm{CD{-}L{\cdot}{\cdot}{\cdot}M^{m+}{\cdot}{\cdot}{\cdot}F}} \rightleftharpoons \underset{\text{b}}{\begin{array}{c}\mathrm{CD{-}L}\\ \mathrm{S}\\ \mathrm{M}^{m+}\\ \mathrm{F}\end{array}} \quad (1)$$

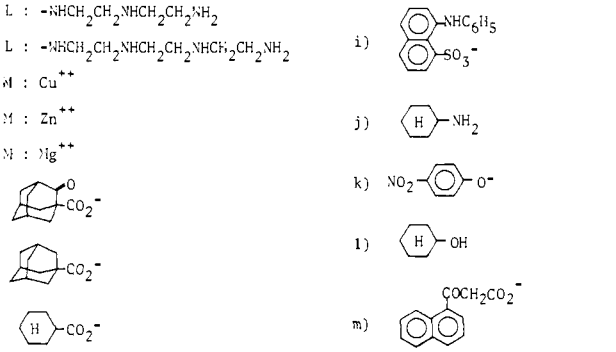
ion, and F, catalytic moiety; binding interactions are shown by dotted lines). The significance of metal–substrate interaction during the binding, as well as the catalytic step, is proposed for most of metalloenzymes, though not yet fully characterized in details.[7]

We wish to report that cyclodextrins functionalized with polyamines (I) strongly interact with such metal ions as Cu^{2+}, Zn^{2+} or Mg^{2+}, and the resultant cyclodextrins *flexibly* capped by metal ions (II) now can bind several anions with hydrophobic moieties (IIIf–m) much more strongly than parent or functionalized cyclodextrin I without metal coordination, as shown in Table I, providing an excellent metalloenzyme model endowed with specific metal–substrate binding interaction, a requisite for the specific catalytic function of most metalloenzyme.



(2)

a) L : $-NHCH_2CH_2NHCH_2CH_2NH_2$
b) L : $-NHCH_2CH_2NHCH_2CH_2NHCH_2CH_2NH_2$
c) M : Cu^{++}
d) M : Zn^{++}
e) M : Mg^{++}



Remarkably enhanced binding of hydrophobic anions by the present metallo hosts in *water* may be due to *double recognition* as schematically shown in eq 3.

$$\mathrm{CD{-}L} + \mathrm{M}^{++} + \ddot{\mathrm{S}} \rightleftharpoons \begin{array}{c}\mathrm{CD{-}L}\\ \mathrm{S}\text{---}\mathrm{M}^{++}\end{array} \quad (3)$$

Pure sample of primary tosylate of β-CD[8] was converted to β-CD functionalized with polyethylenepolyamine by treatment with the amine to be introduced at 50 °C for 5 h. Silica gel chromatography and/or Sephadex G-15 gel filtration (0.1–2 N, NH_4OH) gave pure cyclodextrinpolyamines I.[9] Metal binding by *apohost* I was quantitatively investigated in the case of Cu^{2+} by measuring the characteristic absorption of the Cu^{2+} complex at 660 and 257 nm in 0.1 N aqueous NaOH.[10] The association constant obtained from the Benesi–Hildebrand plot was $10^{17.9}$, which does not differ seriously from that of the diethylenetriamine–Cu^{2+} complex, $10^{18.8}$. All of the cyclodextrinpolyamines I (*apohost*) used are desirable ligands strong enough to bind metal ion, forming *holohost* as shown in Table II. That the holohost II binds another hydrophobic ligand strongly (and specifically) was shown by the fluorescence measurements with 1-anilino-8-naphthalenesulfonate, 1,8-ANS (red shift of the fluorescence maximum and/or remarkable increase in fluorescence intensity).[4]

Dissociation constants of the ternary complex IV without chromophore or fluorophore were obtained from competition with 1,8-ANS binding. The holohost, IIa,d, binds adamantan-2-one-1-carboxylate 330 times stronger than β-CD (Table I). Such binding enhancements were seen only for the holohosts in complexing with hydrophobic anions of the types $-CO_2^-$, $-SO_3^-$, and $-O^-$, while the corresponding apohosts were only two to three times more effective than unsubstituted β-CD.

Despite no appreciable difference in the K_d constant between cyclohexanol complex of holohost IIa,d and that of β-CD,