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Multidentate carborane-containing Lewis acids and their chemistry: mercuracarborands

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Contents

Abstract

Macrocyclic Lewis acidic hosts with structures incorporating electron-withdrawing icosahedral carboranes and electrophilic mercury centers bind a variety of electron-rich guests. These compounds, the so-called mercuracarborands, are synthesized by a kinetic halide ion template effect that affords tetrameric cycles or in the absence of halide ion templates, cyclic trimers. Both types of mercuracarborands form stable host–guest complexes with anionic and neutral electron-rich molecules. The multidentate structure of mercuracarborand hosts has made these unique molecules ideal for catalytic and ion-sensing applications as well as for the assembly of supramolecular architectures.
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1. Introduction

The recognition of supramolecular host–guest complexes as a discrete branch of chemistry evolved from the discovery of crown ethers and other cation-binding molecules [1]. Since that time, the search for electrophilic "anti-crown" species, which bind anions or electron-rich molecules, has been successfully pursued through a variety of independent research efforts. This new class of intensely sought multidentate, anion-encapsulating molecules is comprised of organic, inorganic, and organometallic subclasses [2]. The application of organometallic chemistry to anion complexation is noteworthy in that it exemplifies the possibility of another synergistic relationship between organic and inorganic chemistry.

Two of the three isomeric icosahedral carboranes, specifically *closo*-1,2-$C_2B_{10}H_{12}$ (*ortho*) and *closo*-1,7-$C_2B_{10}H_{12}$ (*meta*) carborane, are ideal building-blocks for these types of structures. Both cages are electron-deficient and provide $-I$ substituent effects at their carbon vertices [3]. Regiospecific substitution chemistry of the cages is well-defined and building off the carbon or boron vertices is well-established [4]. The reaction of C,C′-dilithio-carborane derivatives with mercury(II) centers has produced cyclic structures that bind halide ions as well as a variety of other anions and electron-rich molecules. Members of this new class of anion-binding, multidentate macrocycles have been identified by our laboratory as "mercuracarborands". The synthesis, complexation, supramolecular derivatives and applications of mercuracarborands provide the foci of this review.

2. Synthesis of mercuracarborands

Functionalization of the icosahedral carboranes is easily accomplished at either the carbon or the boron vertices. The hydrogen atoms of the CH vertices can be removed by strong bases, such as alkyllithuim reagents, in organic solvents. Once deprotonated, the anionic carbon vertex is quite basic and serves as an effective nucleophile. Numerous publications from this laboratory and others have exploited this mode of reactivity to synthesize novel carborane-containing structures including such recently investigated species as carborarods [5], carboracycles [6], and oligomeric phosphodiesters [7] among others. A general reaction pathway using 1,2-dilithio-*ortho*-carborane and mercury(II) centers for the synthesis of mercuracarborands is presented in Scheme 1.

Carboranes are "three-dimensional aromatic" molecules and undergo electrophilic aromatic substitution reactions not unlike traditional arenes. As in the case of aromatic organic molecules, substitution occurs at regiospecific locations on the cage. For example, when treated with iodine or iodine monochloride in the presence of aluminum chloride, *ortho*-carborane is substituted at the 9 and 12 positions, replacing B–H
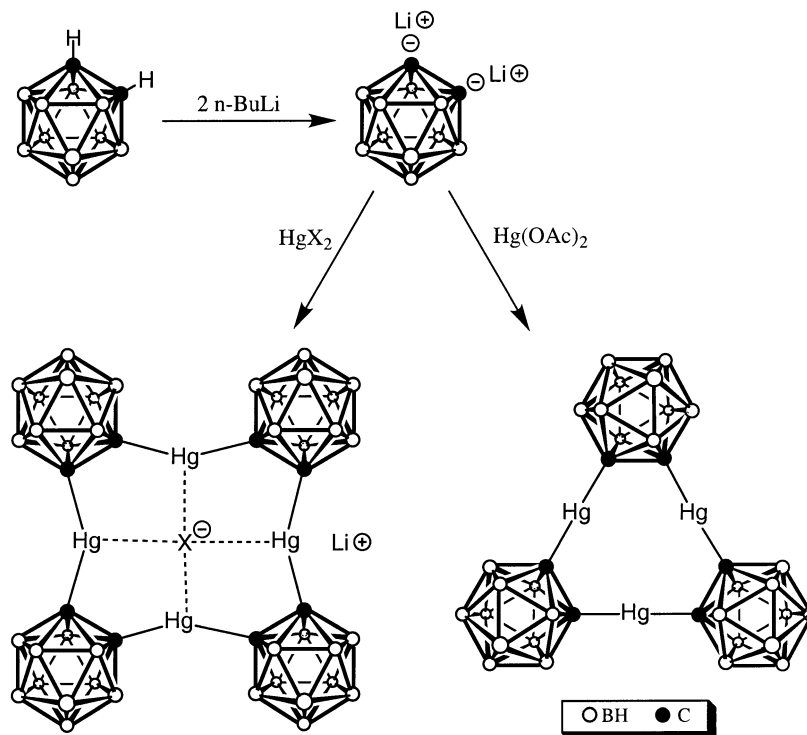
Scheme 1.

with B–I in high yield [8]. Similarly, treatment of *meta*-carborane under the same reaction conditions produces 9,10-diiodo-1,7-$C_2B_{10}H_{10}$ [8b]. The regiospecificities of both reactions are controlled by the electron-withdrawing effect of the carbon vertices. These diiodocarborane species are utilized as precursors in the synthesis of the corresponding dialkylcarboranes employed in mercuracarborand syntheses.

2.1. Discovery of an anion template effect: [12]mercuracarborand-4

The first mercuracarborand to be synthesized was the tetrameric [12]mercuracarborand-4 [9]. This was accomplished by reacting 1,2-dilithio-1,2-$C_2B_{10}H_{10}$ with mercury(II) chloride in ethereal solvent. The tetrameric cycle formed in 75% yield while virtually no oligomeric carboranyl–mercury compounds were detected. A single crystal X-ray diffraction study of the mercuracarborand tetramer containing a complexed chloride anion was determined. The square-planar coordination geometry of the chloride ion was, at the time, unprecedented. In addition, this structure also demonstrated the largest known angle deviation from 180° observed in an R_2Hg derivative.

In a subsequent publication [10], it was found that the [12]mercuracarborand-4 cycle with two bound iodide ion guests could be synthesized in a similar manner using mercury(II) iodide. It was also discovered that this cycle could be freed of complexed iodide ions by treatment with silver acetate without decomposition of the mercuracarborand. Instead of the planar structure previously determined for the complexed tetramer, the parent cycle adopts a folded or "butterfly" pattern once the guests are removed (Fig. 1) [11]. Aside from the solid-state structure, conformational changes or ring-flips of the folded cycle were monitored by ^{199}Hg-NMR studies in deuterated acetone.

The interesting fact that neither oligomeric molecules nor mercuracarborand cycles smaller or larger than the tetramer were observed in the above reactions resulted in the proposal that an anion template effect mediated the reaction (Scheme 2). By definition [12], if in the presence of a template a reaction leads to products that do not form without the template, the reaction is mediated by a kinetic template effect. The initial reaction of dilithiocarborane (**A**) with the mercury center produces the reactive species, 1-Li-2-HgX-1,2-$C_2B_{10}H_{10}$ (**B**). From this point, if X is a halide ion, the reaction may proceed via two possible pathways. Intermediate **B** can react with another equivalent of itself to produce the dimeric structure **D**. This species is held in a crescent shape by the halide ion, which is coordinated between the two bound mercury centers. The template ion facilitates a cyclic geometry as the reaction continues by reacting with two more equivalents of **B** to ultimately
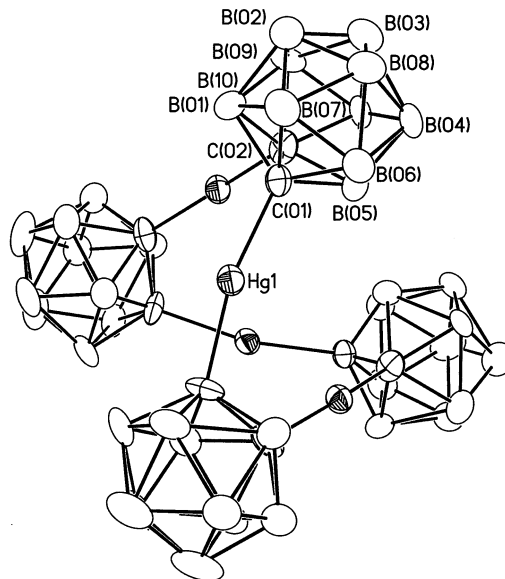

Fig. 1. Structure of the framework of [12]mercuracarborand-4·$(THF)_4\cdot(H_2O)_2$ (ORTEP, with hydrogen atoms, H_2O, and THF molecules removed for clarity).

form the tetramer. If the initially generated **B** reacts with HgX_2 instead of itself, intermediate **C** is formed. This pathway is also mediated by a template anion that is coordinated to two mercury centers bound to a carborane. Intermediate **C** can react with **A**, following along the aforementioned pathway or it can react with **B** to produce the new intermediate **F**. Again the process continues until [12]mercuracarborand-4 is formed. This was the first example of an anionic guest acting as a template for host construction ever reported.

If X in the above scheme is a weakly coordinating anion such as acetate ion, no template effect exists and a trimeric cycle or linear oligomeric compounds having no bond angle strain at mercury would predominate. This was later proven to be the case [13] and is discussed in Section 2.2. The results of the [12]mercuracarborand-4 and later [9]mercuracarborand-3 studies support the hypothesis that the tetrameric cycle is formed via a kinetic template effect. Further proof of an anion template effect will be discussed in Section 3.

2.2. Without template: [9]mercuracarborand-3

The synthesis of another branch of the mercuracarborand tree, namely the trimeric [9]mercuracarborand-3 series, was accomplished via a similar pathway to the [12]mercuracarborand-4 cycles, but with the absence of the template effect [13]. When the noncoordinating mercury(II) acetate was reacted with an equal amount of 1,2-dilithio-1,2-$C_2B_{10}H_{10}$ in diethyl ether, the trimeric cycle was formed in 65% yield. No evidence of the tetramer was found. It is not surprising that the trimer is the dominant product under these reaction conditions as
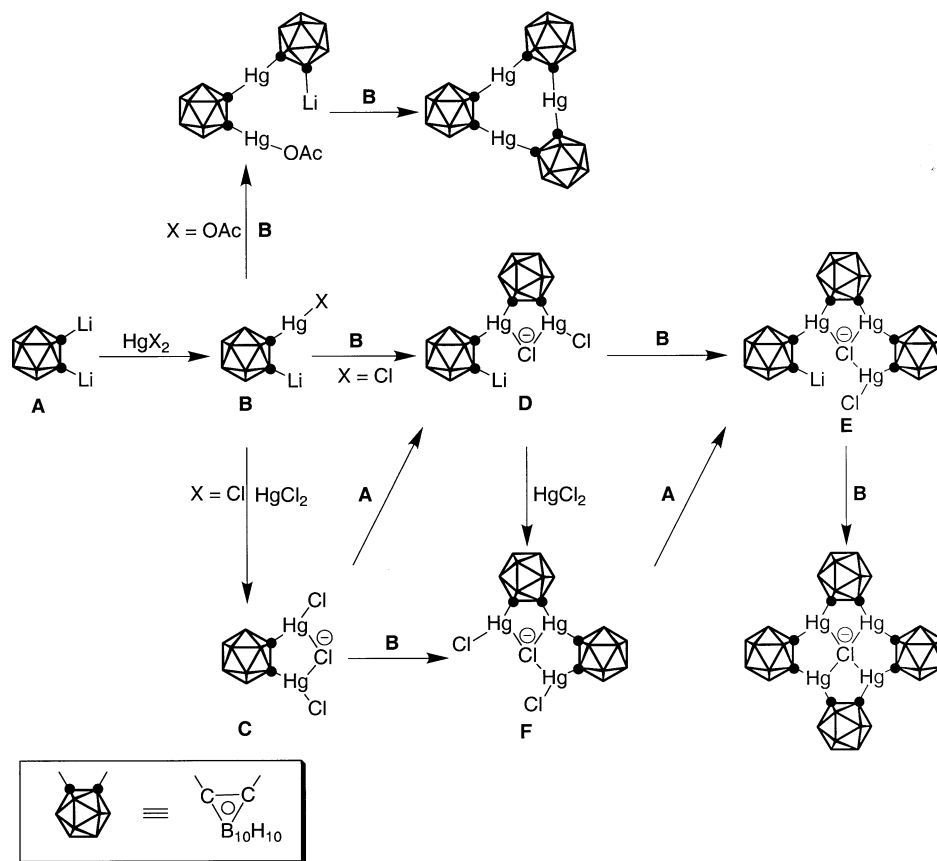
Scheme 2.

the cycle has little angle strain, thus allowing the mercury atoms to form nearly linear bonds. The dominance of trimer over oligomeric products must be due to the fact that the intramolecular ring-closing step is more rapid than an intermolecular step, which propagates oligomeric structure formation.

The empty mercuracarborand trimer was found to be soluble in ether, tetrahydrofuran and acetonitrile. A crystal was grown from acetonitrile and its structure determined by X-ray diffraction. It was discovered that empty [9]mercuracarborand-3 would bind chloride ion in solution forming a stable host–guest complex as evident from ^{199}Hg-NMR studies [13].

2.3. "Inside-out" mercuracarborand

A charge-reverse or "inside-out" trimeric mercuracycle was synthesized with the mercury atoms which link the structure bound to the boron atoms in the 9,10-positions of meta-carborane cages (Fig. 2) [14]. The cage carbons of the meta-carborane modules were protected in a standard manner by reacting 1,7-dilithio-1,7-$C_2B_{10}H_{10}$ with tert-butyldimethylsilyl chloride (TBDMSCl) [15]. The protected carborane was functionalized at the 9,10-positions by reaction with mercury oxide in trifluoroacetic acid [16]. The –HgOCOCF$_3$

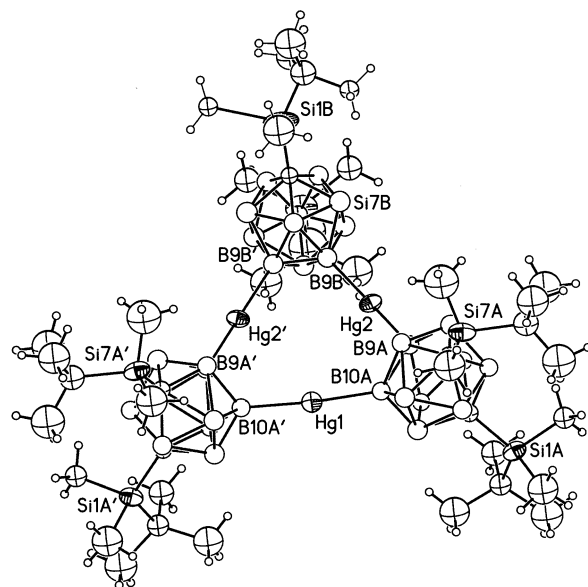Fig. 2. ORTEP plot of "inside-out" trimeric mercuracycle (cage hydrogen atoms removed for clarity).

appendages were quantitatively converted to –HgCl groups by treatment with sodium chloride [17]. Utilizing a known reaction with lithium aluminum hydride [18], the "inside-out" trimeric cycle was obtained in 70%

yield. This synthetic scheme for cycle construction exemplifies the versatility of carborane cages as modules in the construction of molecular architecture.

Complexation of halide anions with the "inside-out" mercuracycle was unsuccessful, as expected, due to the strong electron donating character of the cage at the 9,10-positions, which effectively reduces the electrophilicity of the mercury centers. It was found, however, that the reverse cycle is more resistant to nucleophilic attack than the related C–Hg–C trimeric mercuracarborands. The "inside-out" mercuracycle is stable in the presence of thiophenolate ion whereas [9]mercuracarborand-3 is not.

3. Substituted mercuracarborands

The unsubstituted mercuracarborands exhibit an impressive ability to tightly complex anions. Once these guest ions are bound they are held quite strongly and do not readily dissociate in solution. Before applications could be sought for mercuracarborands, possibly in the realm of catalysis, the solubility of the cycles required modification. The unsubstituted cycles are only soluble in ethereal and other coordinating polar organic solvents such as acetone and acetonitrile, which would limit their usefulness as homogeneous catalysts. They are essentially insoluble in hydrocarbons. To expand the solubility of mercuracarborands in hydrocarbon solvents, carborane cage-substitution was employed prior to cycle formation.

3.1. Carborane cages substituted at 3-(or 6-)position

Utilizing a reaction discovered by our laboratory in the 1960s [19], 3-phenyl-1,2-$C_2B_{10}H_{11}$ was synthesized for use as a hydrophobically substituted carborane building block for the synthesis of possible hydrocarbon-soluble mercuracarborands. The synthesis was achieved in 85% yield by reacting the disodium salt of the *ortho*-dicarbollide ion, [*nido*-7,8-$C_2B_9H_{11}$]$^{2-}$, with phenylboron dichloride. This compound was converted to the corresponding dilithium salt by treatment with butyllithium followed by templated ring closure upon the addition of mercury(II) iodide [20]. The lithium salt of the 1,2-alternate isomer of tetraphenyl [12]mercuracarborand-4·iodide was exclusively formed as one of four possible diastereomers in 85% chemical yield (see Section 3.1.1). The product was soluble in dichloromethane and crystals were grown from an ether/pentane solvent mixture. The question of whether the previously demonstrated silver ion mediated decomplexation procedure could be used to remove the encapsulated iodide ion from this very encumbered environment was examined and anion removal successfully accomplished.

3.1.1. Proof of an anion template effect

An alternate purpose for choosing cages functionalized at the 3- (or 6-) position was that the resulting mercuracarborand/halide ion complexes would be diastereomeric. If the ratio of product diastereomers was dependent upon the identity of the halide ion employed, a template mechanism would be demonstrated. The solid-state structure of mercury(II) iodide product described above revealed an alternating "down, up, down, up" pattern of the cycle which literally caged the iodide anionic guest (Fig. 3a and b) [20]. No evidence of the other three possible isomers was found. The phenyl ring in the 3-position of the carborane cage interacts with the large iodide ion during ring formation forcing the next cage to adopt the least sterically crowded conformation as evident from the absence of any products containing adjacent cages with phenyl substituents on the same side of the ring. If mercury(II) chloride was used to synthesize the tetraphenyl tetramer, the smaller templating anion with less steric influence allowed three of the four possible stereoisomers to form, with only the all up (or all down) isomer not represented [21]. The different diastereomeric product distributions, dependent on which mercury dihalide reagent was used, proves that the halide ion is present during the ring-forming steps of the mechanism which establish the product stereochemistry proving that the halide ion is a template for ring formation.

Dilithio-3-phenyl-1,2-$C_2B_{10}H_9$ was reacted with mercury(II) acetate in an effort to produce the corresponding trimeric cycles [21]. This attempt failed to produce trimeric cycles presumably because two adjacent cages would be forced to have their appended phenyl rings located on the same side of the ring, which is sterically impossible for such a small cycle. Only an acyclic trimeric oligomer with "up, down, up" positioning of the phenyl rings was isolated, due to steric crowding. This structure resembles an intermediate in the proposed cyclization mechanism. Together, these results comprised the first reported example of anion-dependent control of stereochemistry developed during a template-mediated cyclization reaction.

3.1.2. Mercuracarborand complexes as non-coordinating anions

The iodide and chloride ion complexes of the diastereomeric tetraphenyl mercuracarborands have similar characteristics as seen in their crystal structures. In all cases the four mercury atoms are in the same plane with the anion sitting above or below that plane which forces the host–guest complex to adopt a saddle-like shape (Fig. 4) [21,21]. These complexes are "non-coordinating anion" candidates since the only nonbonding electron pairs are associated with the sterically encumbered halide ions. The lipophilic barrier created by the
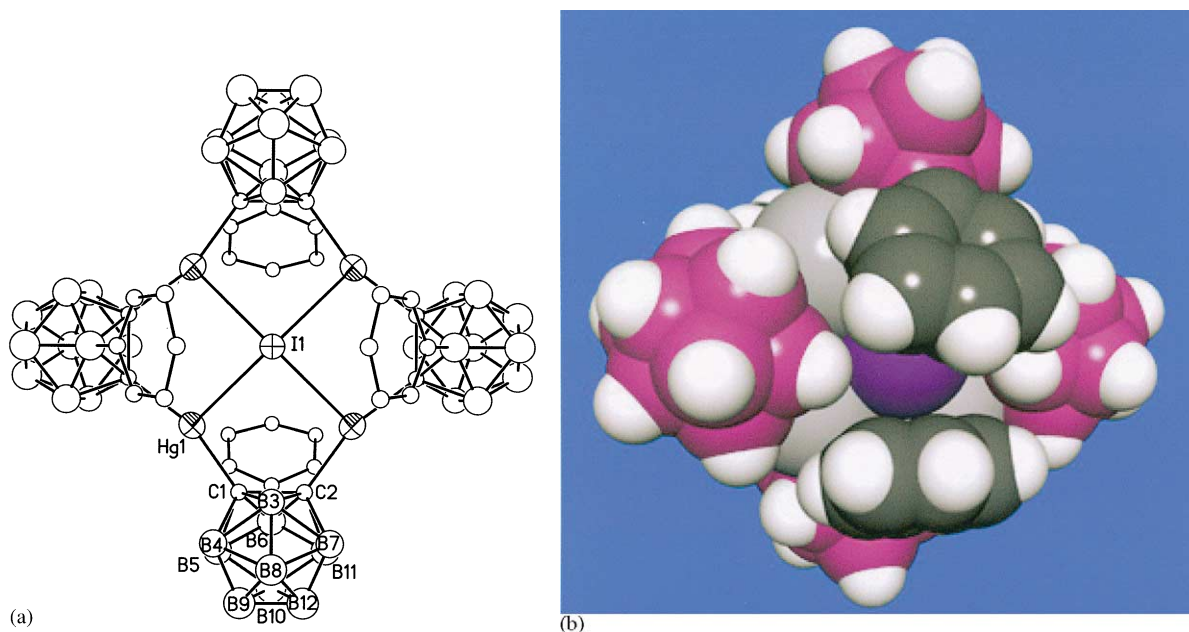
Fig. 3. ORTEP plot (a) and space-filled representation (b) of the 1,2-alternate tetraphenyl-[12]mercuracarborand-4·I⁻ complex.

encapsulating phenyl rings protects the coordinated anion from the cationic counter-ion.

3.2. Carborane cages substituted at 9,12-positions

The most useful method of increasing mercuracarborand solubility without perturbing the binding cavity of the mercuracarborand was to employ 9,12-disubstituted-1,2-$C_2B_{10}H_{10}$ cages as precursors. Substitution of *ortho*-carborane in this fashion was accomplished by coupling 9,12-diiodo-*ortho*-carborane with an alkyl or aryl Grignard reagent mediated by a palladium(II) catalyst [8b]. The first mercuracarborand of this type to be synthesized was octaethyl-[12]mercuracarborand-4 [22]. This mercuracarborand was synthesized as its complex with two iodide ion guests and the free host was soluble in acetone, acetonitrile and methylene chloride.

Hydrocarbon solubility (excluding chlorinated solvents) was achieved when mercuracarborands derived from methylated *ortho*-carborane were investigated [23]. Cycles incorporating 9,12-dimethylated cages had solubility properties resembling those of the ethylated cycles.

The first completely hydrocarbon soluble mercuracarborands were based on 8,9,10,12-tetramethyl-1,2-$C_2B_{10}H_8$ as the building module. This cage was synthesized by heating *ortho*-carborane and ten equivalents of methyl iodide in triflic acid for 4 days [23]. Reaction of this new substituted cage with mercury(II) iodide afforded hexadecamethyl-[12]mercuracarborand-4 as its diiodide complex. This host–guest species was soluble in methylene chloride, toluene and benzene [23].

The goal of hydrocarbon solubility was also extended to include the trimeric [9]mercuracarborand-3 cycles. Hexamethyl-[9]mercuracarborand-3 was synthesized from 9,12-dimethyl-1,2-$C_2B_{10}H_{10}$ and found to have increased solubility in methylene chloride and toluene [24].

4. NMR studies of halide ion complexation/decomplexation

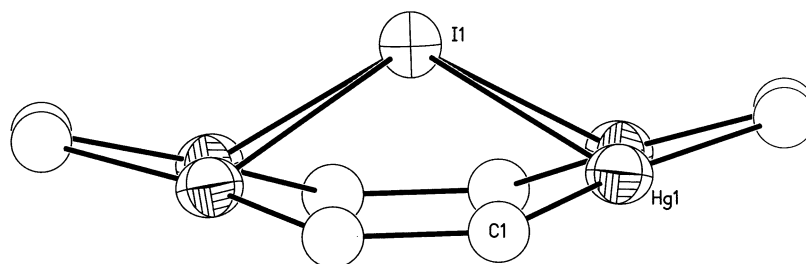Both X-ray diffraction and ^{199}Hg-NMR studies have confirmed the complexation of a variety of anionic

Fig. 4. Side view of the 1,2-alternate tetraphenyl-[12]mercuracarborand-4·I⁻ complex showing only the 12-membered ring and the complexed iodide ion (one of two possible locations) for clarity.

guests by mercuracarborand hosts. Although the solid-state structures of the host–guest complexes have lent insight to their supramolecular architecture, the strength of the associative electronic binding interactions and the stability of such structures in solution remained as unknowns. The most illustrative data concerning anion binding by mercuracarborand hosts has been obtained from [199]Hg-NMR studies of complexation. Other NMR methods, using ^{1}H, ^{13}C, or [11]B nuclei, are not sensitive to the guest presence, but [199]Hg-NMR is highly sensitive to small changes in the electronic environment surrounding the mercury centers [25]. Furthermore, complexation or decomplexation reactions can easily be monitored and the maximum occupancy of the cycles determined as well as the stoichiometries of intermediates.

A typical example in the use of [199]Hg-NMR techniques to monitor complexation/decomplexation of the unsubstituted [12]mercuracarborand-4 was presented in the original cycle decomplexation study and is depicted in Scheme 3 [11]. The diiodide complex was treated with silver acetate to remove the two bound guest atoms. Analysis of the [199]Hg-NMR spectra obtained in different solvents showed a solvent dependence of the noncomplexed mercuracarborand. Broad signals at $\delta = -1205$ in acetone and -1305 in THF were observed and explained as solvent molecule association with vacant coordination sites of the mercury atoms [11,26].

$$cycle \overset{I^-}{\rightleftharpoons} cycle \cdot I^- \overset{I^-}{\rightleftharpoons} cycle \cdot I_2^{2-}$$
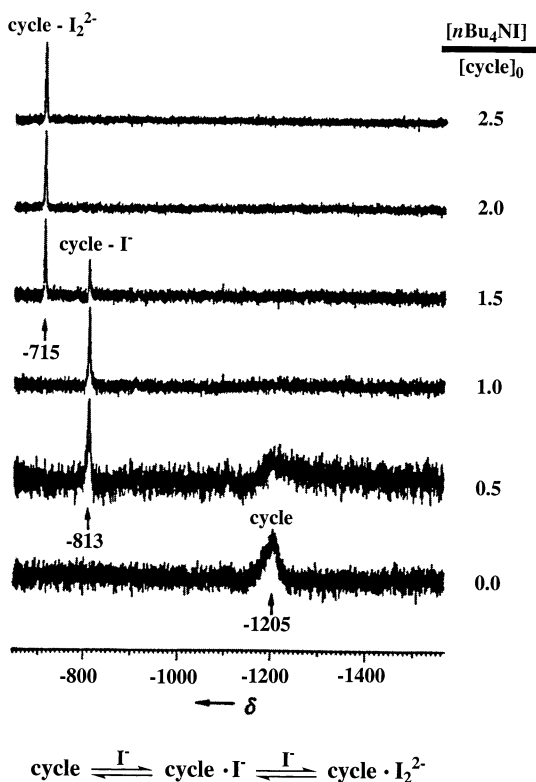
Scheme 3.

This proposal was further supported by the solid state structure of the decomplexed tetrameric cycle which, when obtained from wet THF, contained four THF molecules and two water molecules coordinated to the four mercury atoms. The breadth of the resonances is due to dynamic ring flip of the "butterfly" structure on the NMR timescale.

Systematic addition of tetrabutylammonium iodide, TBAI, to the decomplexed mercuracarborand in deuterated acetone (Scheme 3) produced a pronounced downfield shift of the mercury signal. When one equivalent of TBAI was added, the signal at $\delta = -1205$ disappeared and a sharp resonance representing the monoiodo-complex formed at $\delta = -813$. Further addition of another equivalent, or more, of TBAI caused the loss of the resonance at $\delta = -813$ and the formation of a new resonance at $\delta = -715$ which corresponded to the diiodide complex. Once the host–guest complexes form, they show no solvent or concentration dependence, although different halide complexes exhibit characteristic chemical shifts. In deuterated acetone, the monobromide complex of unsubstituted [12]mercuracarborand-4 has a mercury signal at $\delta = -1010$ [27] and the monochloride complex has a signal at $\delta = -1077$ [9].

Monitoring the silver mediated decomplexation of the octamethyl-[12]mercuracarborand-4·diiodide complex in acetone by [199]Hg-NMR led to the discovery of another host–guest complex not seen in the unsubstituted cycles [23]. Treatment of the diiodide complex with one equivalent of silver acetate removed one iodide ion guest, but the signal for the diiodide complex ($\delta = -667$) did not completely disappear once the new signal at $\delta = -765$ for the monoiodide complex began to form. Addition of another half of an equivalent of silver acetate resulted in a signal at $\delta = -846$. This was attributed to an unprecedented 2:1 host to guest sandwich complex seen only in solution. Final addition of excess silver cation resulted in the decomplexed cycle with a signal at $\delta = -1145$.

5. Supramolecular solid-state structures

Mass spectroscopy and [199]Hg-NMR characterization data for the mercuracarborand host–guest complexes have shown that the bound structures are quite stable in solution. The solid state structures of the same compounds have in some cases provided clear evidence for what was observed in NMR studies, and in other cases new molecular architectural constructs have been found. The single crystal solid-state structures of mercuracarborands have expanded the boundaries of molecular self-assembly.

5.1. Mono- and dianionic complexes

5.1.1. Halide ion guests

The most extensive subcategory of trimeric and tetrameric mercuracarborand solid-state structures is comprised of the mercuracarborand·halide ion complexes. Both [12]mercuracarborand-4 and [9]mercuracarborand-3 cycles have been crystallized as the mono- and dihalide host–guest complexes and sometimes as 2:1 host/guest sandwich structures.

The first reported mercuracarborand structure was that of the unsubstituted [12]mercuracarborand-4·chloride ion complex [9] which was described earlier in this review. Subsequent publications reported other monochloride complexes [21,29] as well as the mono- [27] and dibromide [23] and mono- [20,21,28,29] and diiodide [10,23,27–30] complexes of various (substituted and unsubstituted) [12]mercuracarborand-4 hosts. Comparing the monohalide ion complexes of [12]mercuracarborand-4 cycles, it was found that Cl^- was the only ion small enough to fit within the plane formed by the four mercury centers. The corresponding monobromide ion complex contains the anion partially displaced above (or below) the mercury plane (described as half-occupancy) [27]. The structure of the monoiodide complex of a [12]mercuracarborand-4 host was only determined in the case of the sterically encumbered tetraphenyl cycle with the appended phenyl rings occupying the 3- (or 6-) position of each *ortho*-carborane cage as the 1,2-alternate diastereomer [20]. As described earlier in this review, the iodide ion was completely displaced above (or below) the mercury plane causing the structure to adopt a saddle-like shape.

An intriguing aspect of the single crystal structure of the [12]mercuracarborand-4 monobromide ion complex is that the host–guest pairs stack in a staggered fashion with alternating pairs being shifted so as to minimize steric interactions between carborane cages (Fig. 5) [27]. A similar phenomenon was discovered when an attempt to grow a crystal of the sandwich complex (observed by ^{199}Hg-NMR) of octamethyl-[12]mercuracarborand-4 was performed [23]. A "short stack" complex having the stoichiometry of 3:4 hosts/iodide guests was observed (Fig. 6). The stack is made up of three octamethyl-[12]mercuracarborand-4·monoiodide complexes and one distorted "free" iodide ion.

Solid-state structures of diiodide ion [10,23,27–30] and dibromide ion [23] complexes of [12]mercuracarborand-4 acceptors have been determined. All diiodide complexes, regardless of the substituents attached at the 9,12-positions of the carborane cages, have the iodide guests positioned above and below the plane created by the four mercury atoms. The two iodides are laterally slipped away from one another and the ring centroid (Fig. 7). This is probably due to coulombic repulsion of the two anions. The dibromide ion complex
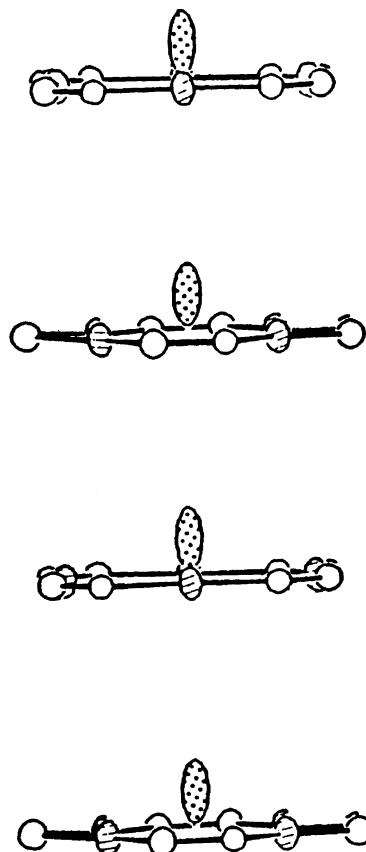

Fig. 5. Stacking diagram of [12]mercuracarborand-4·Br^- in the solid state with hydrogen and boron atoms removed for clarity. Open, striped, and dotted ellipsoids represent carbon, mercury, and bromine, respectively [27].
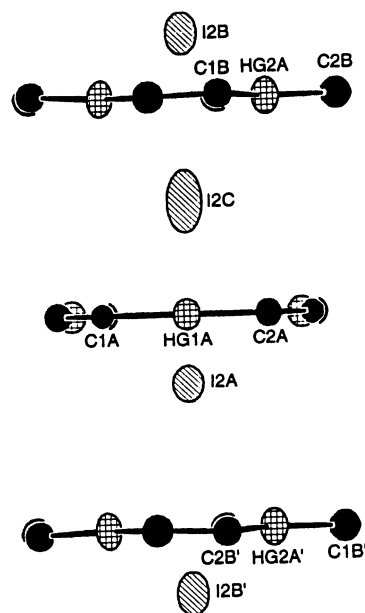

Fig. 6. Stacking diagram of (octamethyl-[12]mercuracarborand-4)$_4$·I_4^{4-} in the solid state with hydrogen and boron atoms removed for clarity. Filled, crosshatched, and striped ellipsoids represent carbon, mercury, and iodine, respectively [23].
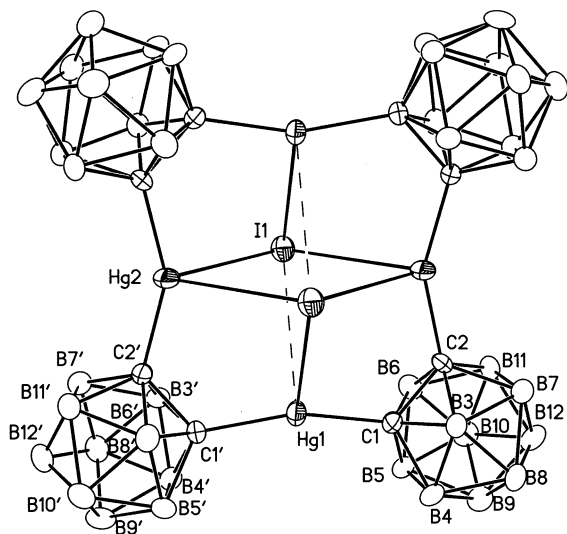
Fig. 7. ORTEP plot of [12]mercuracarborand-4·I_2^{2-} complex (hydrogen atoms removed for clarity).

Fig. 8. ORTEP plot of octaethyl-[12]mercuracarborand-4·$(B_{10}H_{10})_2^{4-}$ with hydrogen atoms removed for clarity except for those bonded to Hg atoms.

of octaethyl-[12]mercuracarborand-4 was similar to other known diiodide ion complexes in that the halide ions were displaced equidistantly above and below the ring plane, but unlike the diiodide ion complexes, there was little to no lateral slippage from the cycle centroid. There is one example of a solid-state structure obtained for a [12]mercuracarborand-4 diiodide ion complex that exhibits peculiar self-assembly characteristics not observed from other substituted cycles [30]. Discussion of this complex and the nanoscale microporous solid structure that it forms appears in a later section of this review.

Trimeric [9]mercuracarborand-3 cycles have also proven to be adept at complexing halide ions, even though synthesis of this class of mercuracarborands must be accomplished without a templating halide. Hexamethyl-[9]mercuracarborand-3 was shown by ^{199}Hg-NMR to complex chloride ion, bromide (one or two ions) and iodide (one or two ions) in solution [24]. The only published structures of halide ion complexes of trimeric mercuracarborands are those of the 2:1 host/guest sandwich structures discussed in detail later in this review.

5.1.2. Other anionic guests

The synthesis of the octaethyl-[12]mercuracarborand-4·diiodide complex was described in an earlier section of this review. Silver ion decomplexation of the host−guest complex followed by complexation of $B_{10}H_{10}^{2-}$ led to the first example of a mercuracarborand complexing an anion other than a halide ion [22]. In solution a 1:1 host/guest complex of the cycle and the anionic borane cage was seen, but the crystal structure revealed a 1:2 host/guest complex (Fig. 8). In a ^{11}B-NMR study, it was found that complexation of the parent cycle with other
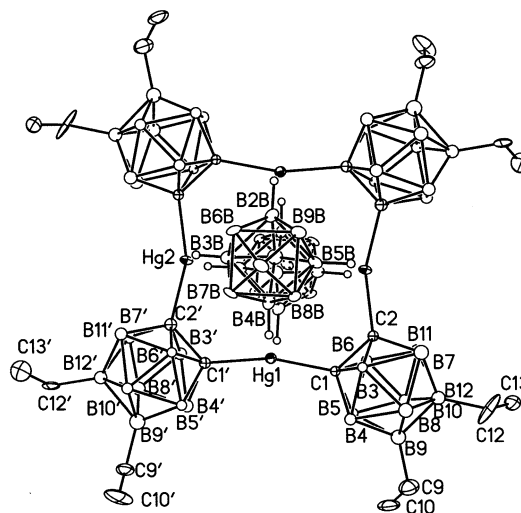
charged boranes ($B_{12}H_{12}^{2-}$) and carboranes (nido-7,8-$C_2B_9H_{12}^{1-}$) does not occur due to the weaker nucleophilic nature of these two cages. Both are larger than $B_{10}H_{10}^{2-}$ and geometrically incompatible with the mercuracarborand cavity. It was discovered, however, that a^2-$B_{20}H_{18}^{4-}$ did form 1:1 and 1:2 host/guest complexes with non-substituted [12]mercuracarborand-4 and octaethyl-[12]mercuracarborand-4. Unfortunately, poor solubility of the complexes prevented their structural characterization. Both $B_{10}H_{10}^{2-}$ and a^2-$B_{20}H_{18}^{4-}$ are held in the [12]mercuracarborand-4 cavity by four three-center two-electron B−H−Hg bonds as seen in Fig. 8. A later publication revealed that octaethyl-[12]mercuracarborand-4 was able to complex nonionic, Lewis basic guests [27]. These results will be discussed in detail in a later section of this review.

Another publication revealed the ability of [12]mercuracarborand-4 to complex a non-halide, anionic guest [31]. Using non-substituted [12]mercuracarborand-4 as the parent cycle, a set of complexes that incorporated nitrate ion (NO_3^-) was prepared. The empty cycle and two equivalents of potassium nitrate were combined with 18-crown-6 in acetone. A 1:2 host/guest complex was formed in 87% yield. The carborane cage carbons were nonplanar in the puckered complex with each of the two nitrate ions (one above and one below the ring) each coordinated through one of their oxygen atoms (Fig. 9a and b).

If the stoichiometry of the complexation reaction was changed and three equivalents of potassium nitrate were used, a completely different structure formed [31]. This new structure also contained two complexed nitrate ions, but the cycle was planar and all three oxygen atoms of each NO_3^- group coordinated to the four mercury atoms of the host (Fig. 10a and b). This was the
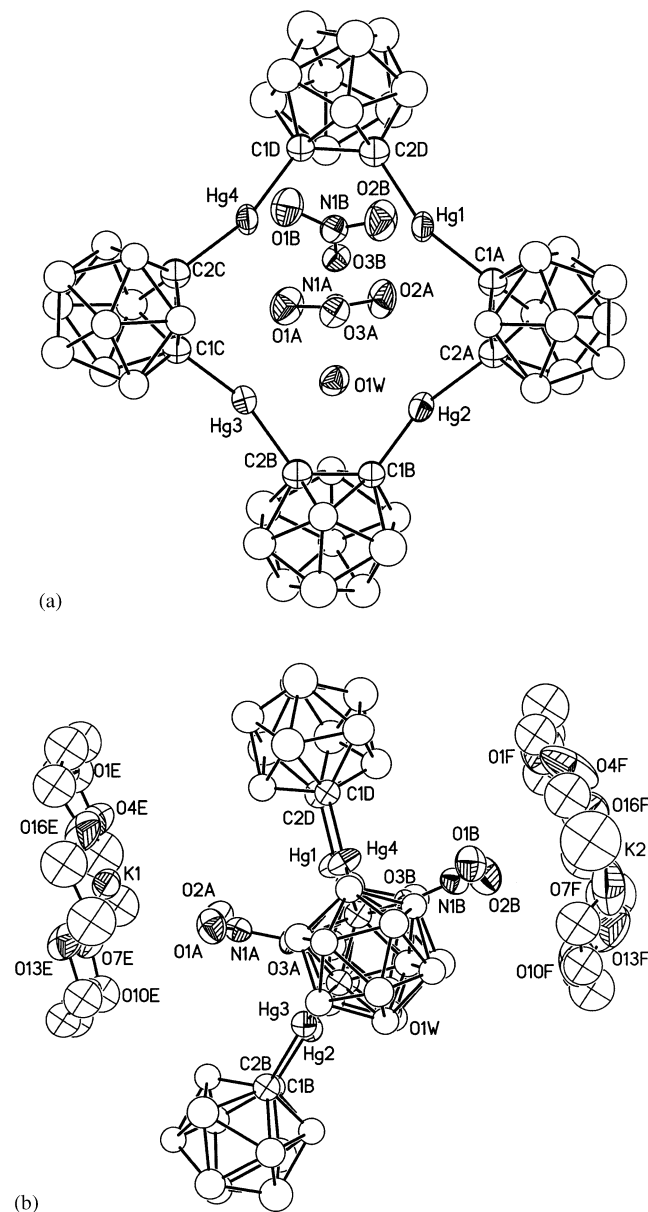
Fig. 9. Top (a) and side (b) views of the structure of [[12]mercuracarborand-4·$(NO_3)_2$·H_2O][K(18-crown-6)]$_2$·H_2O·acetone (ORTEP, with hydrogen atoms, H_2O, and acetone molecules removed for clarity).

first reported example of η^3-coordination of the NO_3^- ion.

5.2. Neutral complexes

The greatly enhanced Lewis acidity of mercury centers attached to electron-withdrawing carborane cages in mercuracarborand structures has allowed these hosts to complex uncharged electron-rich guests [27]. Guest-free octaethyl-[12]mercuracarborand-4 was employed to complex 9,12-diiodo- and 9-ethyl-12-iodo-1,2-$C_2B_{10}H_{10}$ in separate studies. In both cases a 1:2 host/guest

complex formed, similar to the structure of octaethyl-[12]mercuracarborand-4·diiodide described above.

The principal difference in the structures of the iodocarborane guest complexes and the analogous structure of the complex with the anionic iodide guests lies in the spatial arrangement of the iodine atoms above and below the plane formed by the four mercury centers (Fig. 11a and b). In contrast to the diiodide ion complex, there is no lateral slippage of the iodine atoms observed in the iodocarborane complexes even though both exhibit shorter Hg···I distances. This is most likely due to the smaller van der Waals radius of neutral covalently bonded iodine compared to that of anionic iodide causing less steric interference in the former case. The lack of slippage may also have electronic origins
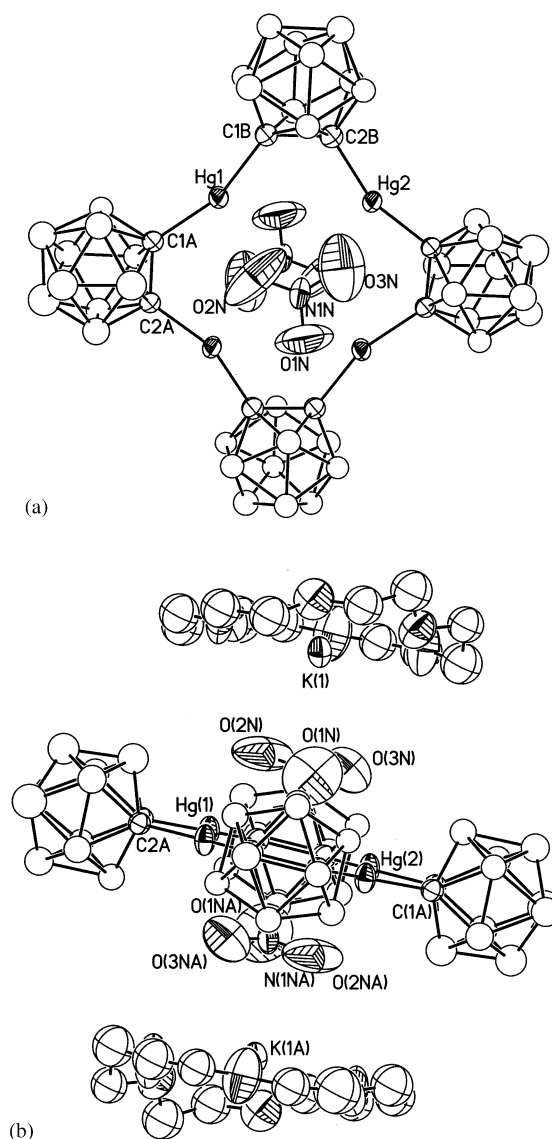

Fig. 10. Top (a) and side (b) views of the structure of two η^3-coordinated NO_3^- molecules in the [[12]mercuracarborand-4·$(NO_3)_2$][K(18-crown-6)]$_2$ complex (ORTEP, with hydrogen atoms removed for clarity).
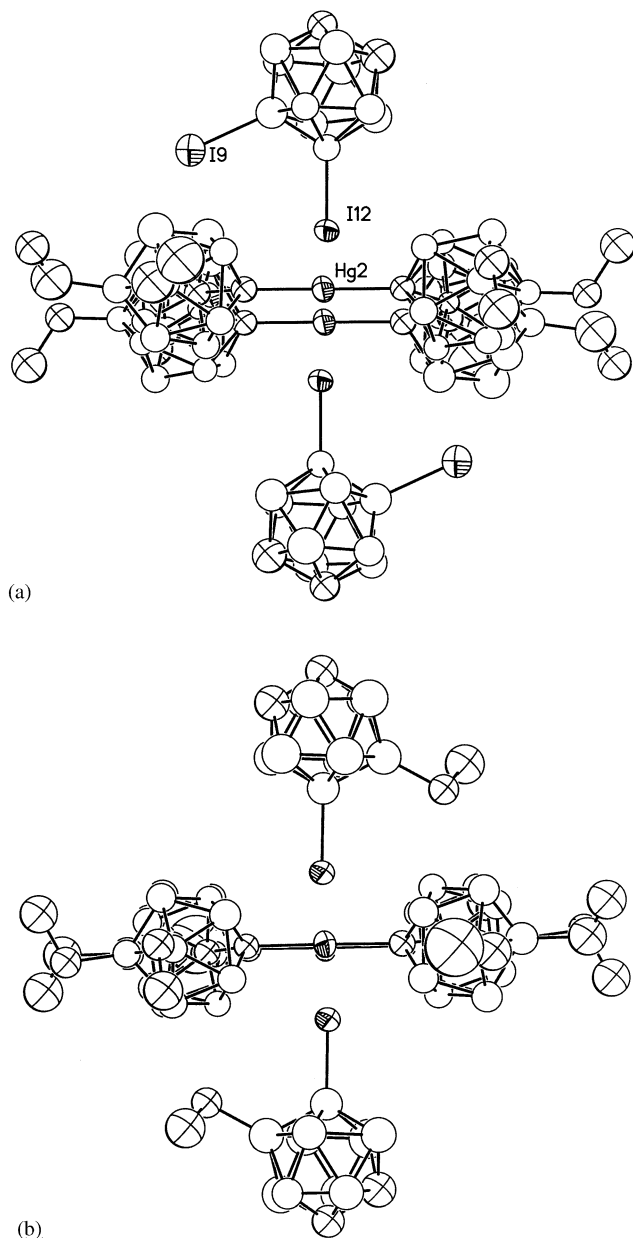
Both sides of the benzene ring encapsulated in the center of the sandwich structure and aligned parallel to the two sandwich mercuracarborand cycles, exhibit π–H hydrogen bonding interactions with one of the two complexed water molecules. Coordination of the water molecule oxygen atoms by the mercuracarborand rings enhances the acidity of the hydrogen atoms, which provides a strong interaction with both π faces of the sandwiched benzene ring. The hydrogen atoms of the complexed water molecules in the structure were disordered and not located, but a firm assumption that they are participating in hydrogen bonding to the benzene ring was justified based on the distance of the
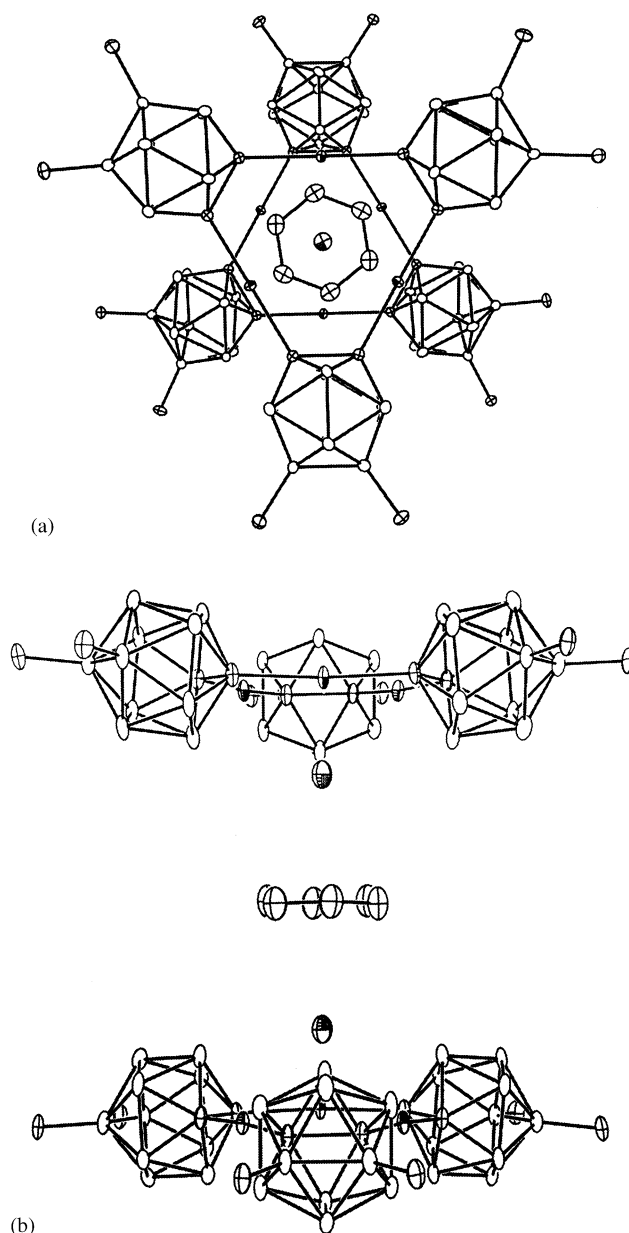

(a)

(a)

(b)

Fig. 11. Side views of octaethyl-[12]mercuracarborand-4·(9,12-I$_2$-C$_2$B$_{10}$H$_{10}$)$_2$ (a) and octaethyl-[12]mercuracarborand-4·(9-C$_2$H$_5$-12-I-C$_2$B$_{10}$H$_{10}$)$_2$ (b) with hydrogen atoms removed for clarity.

explained by the absence of coulombic repulsion of the complexed iodide ions present in the octaethyl-[12]mercuracarborand-4·diiodide complex.

A novel neutral host–guest complex of hexamethyl-[9]mercuracarborand-3 complexing two water molecules and one benzene as a hydrogen-bonded π-sandwich complex has been recently reported [32]. The mercuracarborands are the top and bottom of the sandwich structure and oriented in a staggered fashion with respect to each other (Fig. 12a and b). Each of the water oxygen atoms is η^3-coordinated to all three mercury centers of one of the cycles and located in the interior of the stacked structure.

(b)

Fig. 12. Top (a) and side (b) views of the structure of (hexamethyl-[9]mercuracarborand-3)$_2$·(H$_2$O)$_2$·C$_6$H$_6$ (ORTEP, with hydrogen atoms removed for clarity) [32].
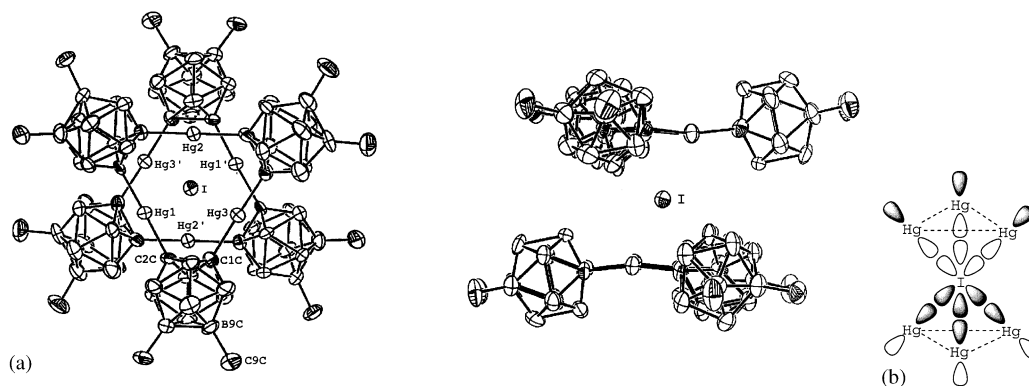
Fig. 13. ORTEP plot (top and side views), with hydrogen atoms removed for clarity (a) and orbital representation illustrating the three-center, two-electron bonds [36] (b) of the (hexamethyl-[9]mercuracarborand-3)$_2 \cdot$I$^-$ sandwich complex [35].

water oxygen atoms from the benzene centroid. The oxygen to benzene distance of 2.99(1) Å is much shorter than either the spectroscopically (3.32–3.35 Å) [33] or theoretically (3.20–3.32 Å) [33,34] determined distances. This is the first solid-state structure of a benzene–water hydrogen bonded complex.

5.3. Sandwich structures

A few examples detailing the unique ability of mercuracarborands to form sandwich structures have been described in this review. In the decomplexation study of the tetrameric octamethyl-[12]mercuracarborand-4·diiodide complex, a unique signal for the 2:1 sandwich complex of host to iodide ion guest was the only species observed in solution by ^{199}Hg-NMR at the 2:1 stoichiometry [23]. The neutral trimer sandwich structure, described above, that complexed one benzene and two water molecules was not observed in solution, but was a reproducible crystalline product supported by single crystal X-ray diffraction studies [32]. Sandwich structures that were stable both in solution as well as in the solid state arose from the complexation of halide ion guests by hexamethyl-[9]mercuracarborand-3 hosts.

The first reported example of the latter phenomenon was the octahedral coordination of iodide ion by two hexamethyl-[9]mercuracarborand-3 cycles [35]. Not only was this the first example of a trimeric mercuracarborand sandwich, whose discovery preceded that of the aforementioned neutral water–benzene complex, but this was also the first example of a 6-coordinate iodide ion in the formal −1 oxidation state ever reported. The trimer sandwich was synthesized in 82% yield by treating guest-free hexamethyl-[9]mercuracarborand-3 with half an equivalent of lithium iodide in acetone. The mercuracarborand hosts crystallized with the trimers in a staggered relationship to each other. This bonding mode alleviated steric repulsion of the carborane cages and maximized the p-orbital overlap between the iodide anion and the six mercury centers forming

three equivalent p$_{Hg}$–p$_{iodide}$–p$_{Hg}$ three-center two-electron bonds (Fig. 13a and b).

Building on the previous results, Lee and Hawthorne later described octahedral coordination of iodide, bromide, and chloride ionic guests by hexamethyl-[9]mercuracarborand-3 hosts forming 2:1 sandwich complexes [36]. In all cases these species were moisture-stable and characterized by crystallography, FAB mass spectroscopy, and ^{199}Hg-NMR, demonstrating the stability of this novel architecture. Each of these structures maintained the staggered hexagram pattern of trimer orientation as expected (Figs. 14 and 15). The interior distance separating the mercuracarborand trimer planes decreases with the decreasing size of the anionic guest: I$^-$ (4.90 Å) > Br$^-$ (4.764 Å) > Cl$^-$ (4.672 Å). In each case, the mercury–halide distances were all nearly equidistant and less than the reported Hg(II)–X$^-$ van der Waals distances [37,38].

5.4. Microporous channels

An interesting solid-state phenomenon was observed in the crystal structure of the dilithium salt of the octaiodo-[12]mercuracarborand-4·diiodide complex [30]. This is the only published report of a mercuracarborand containing 9,12-diiodido-1,2-C$_2$B$_{10}$H$_{10}$ cages. A single crystal was grown from acetone/dichloromethane having a unit cell that incorporated six acetone and four water molecules (Fig. 16). The complex crystallized in the monoclinic space group $C2/m$, with the two iodide anions equidistantly spaced above and below the plane created by the four mercury atoms. As with other diiodide complexes of [12]mercuracarborand-4 cycles, the Hg···I coordination results from orbital overlap of the filled p-orbital of iodide with the empty p-orbitals of the mercury pair favorably arranged for three-centered two-electron bond formation.

Interestingly, the unit cell [Li$_2$(HgC$_2$B$_{10}$H$_8$I$_2$)$_4$·I$_2$] self-assembles into infinite one-dimensional chains held together by novel B–I···Li$^+$···I–B interactions (Fig.
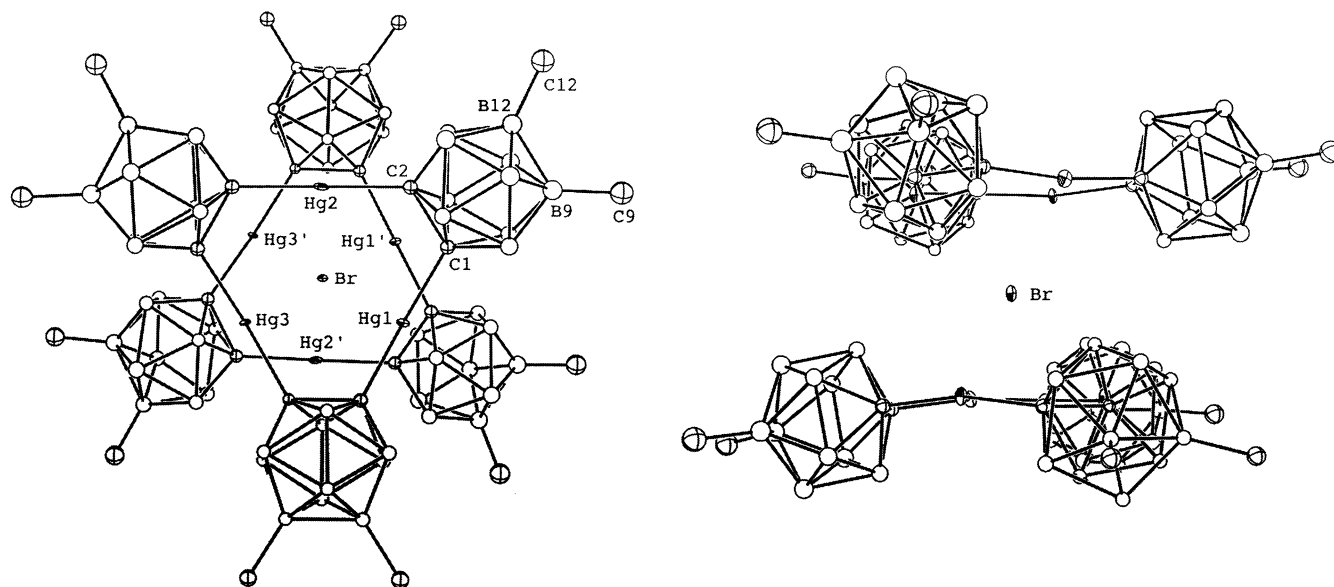
Fig. 14. ORTEP plot (top and side views), with hydrogen atoms removed for clarity of the (hexamethyl-[9]mercuracarborand-3)$_2$·Br$^-$ sandwich complex [36].

17). The resulting nanostructure contains microporous channels occupied by solvent molecules that are arranged perpendicularly to the aforementioned chains. A cross-section of these channels reveals that they are rectangular in shape having the dimensions 8.6 by 11.5 Å, which is in the range of similar channels observed in other metal-organic porous solids [39]. This type of molecular self-assembly has not been previously observed in any known mercuracarborand structures.

6. Applications of mercuracarborands

The synthesis and complexation studies of mercuracarborands have not been merely academic pursuits that expand the realm of carborane chemistry. Binding electron-withdrawing carborane cages to Lewis acidic mercury centers in a cyclic fashion has produced very efficient electrophilic host molecules. These compounds are unique in that they are soluble in most common
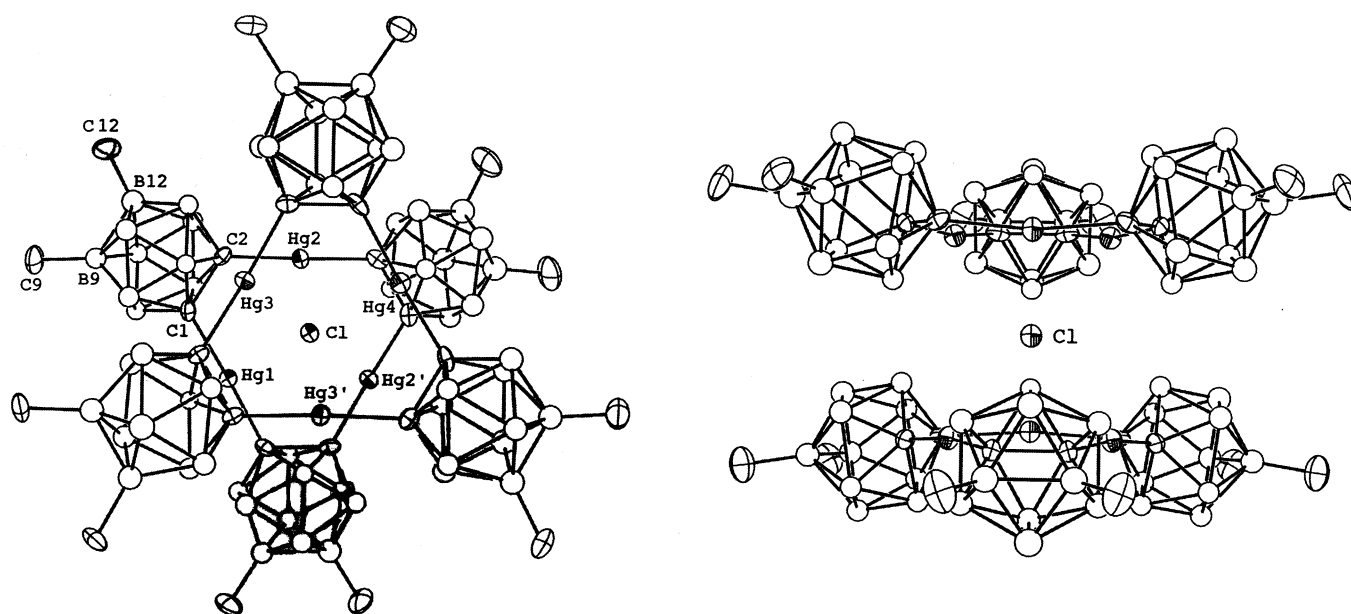

Fig. 15. ORTEP plot (top and side views), with hydrogen atoms removed for clarity of the (hexamethyl-[9]mercuracarborand-3)$_2$·Cl$^-$ sandwich complex [36].
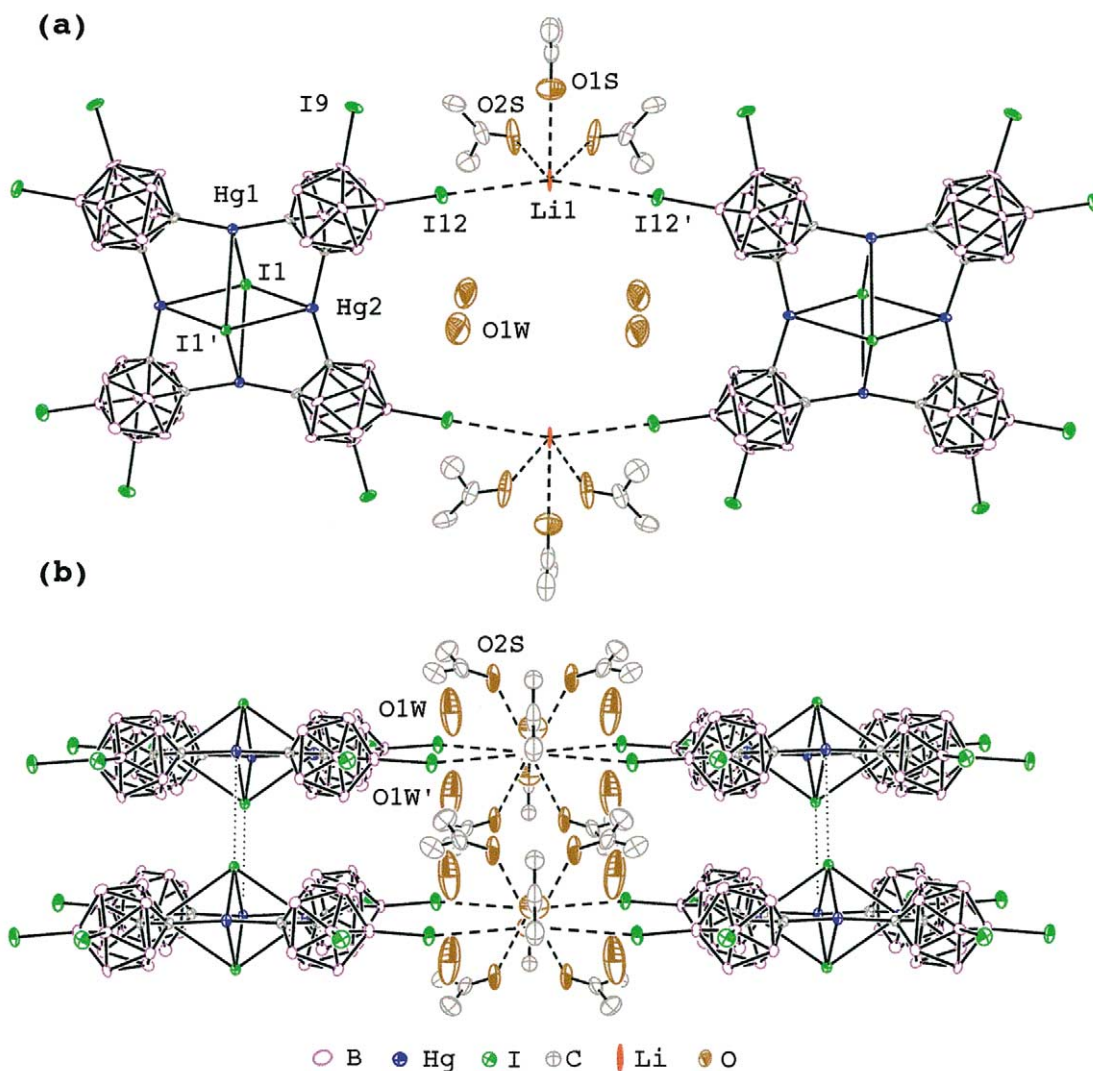
Fig. 16. Top (a) and side (b) views of the crystal packing representation of [Li$_2$((CH$_3$)$_2$CO)$_6$][octaiodo-[12]mercuracarborand-4·I$_2$] ⊃ 4H$_2$O (ORTEP plot, with hydrogen atoms removed for clarity) [30].

organic solvents, stable as solids and in solution for extended periods of time, and they form extremely stable host–guest complexes. The impressive anion-binding capabilities of mercuracarborands have facilitated their use in catalytic and ion-sensing applications. Other novel applications will certainly be found.

6.1. Diels–Alder catalyst

Mercuracarborands have been proven to reversibly bind electron-rich substrates through numerous examples now in the literature. Until highly soluble octamethyl-[12]mercuracarborand-4 and hexamethyl-[9]mercuracarborand-3 were discovered, the use of mercuracarborands as homogeneous Lewis acid catalysts was not actively pursued. The first example demonstrating the utility of mercuracarborands as catalysts was to activate a thionoester dienophile in a

Diels–Alder reaction with cyclopentadiene [40]. This reaction was chosen because it does not normally proceed in the absence of a catalyst and thionoesters bind nicely in a host–guest fashion with mercuracarborands due to the affinity for soft Lewis bases by the soft mercury Lewis acid centers. An attempt to employ methyl crotonate as the dienophile was performed, but no evidence of catalysis or its complexation by mercuracarborands was detected.

As controls, the reaction of O-methyl-trans-2-butenethioate with cyclopentadiene was attempted without catalyst and in the presence of mercury(II) iodide and mercury(II) acetate, all of which failed to yield product. Reactions were then carried out separately with 2 mole% of octamethyl-[12]mercuracarborand-4, hexamethyl-[9]mercuracarborand-3, and bis(closo-9,12-dimethyl-1,2-carboran-1-yl) mercury (Fig. 18) added as catalysts. The tetrameric cycle resulted in complete reaction in the
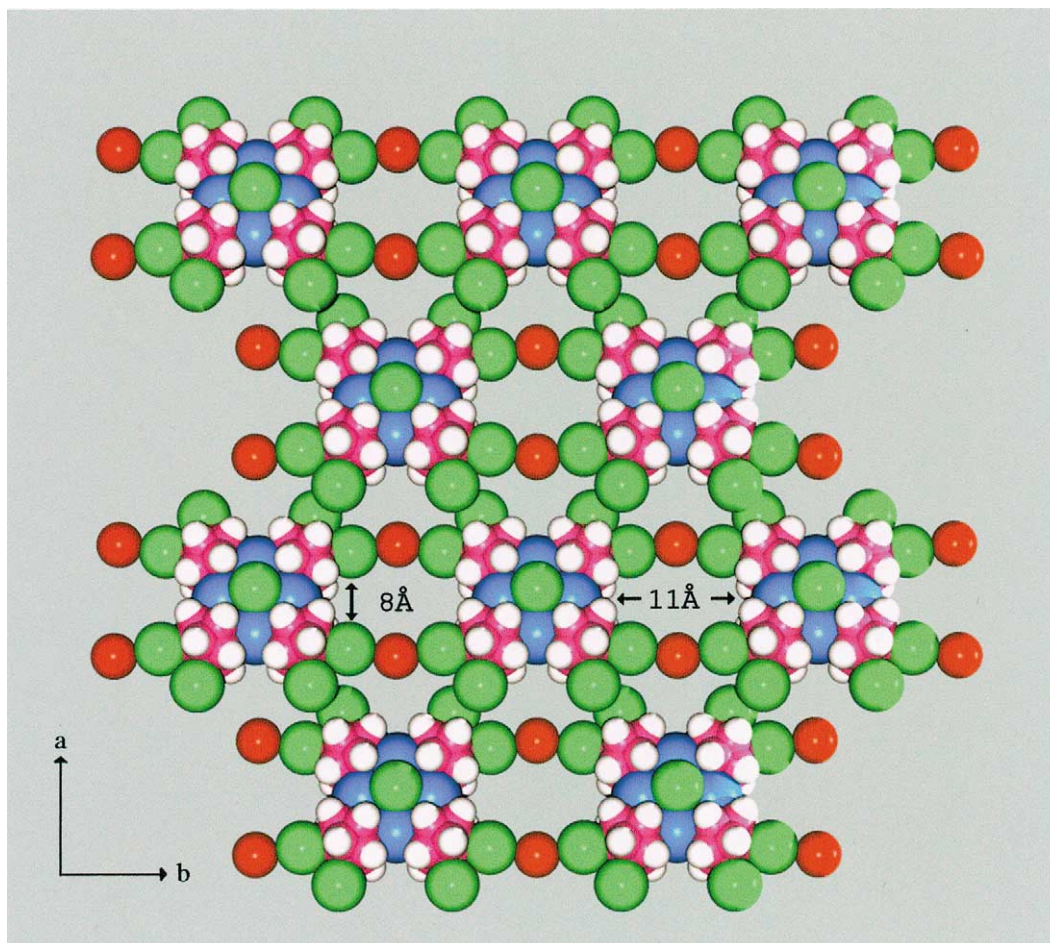
Fig. 17. Space-filled model of the packing lattice of Li$_2$[octaiodo-[12]mercuracarborand-4·I$_2$] (acetone and water molecules are removed for clarity). Color code: B, pink; H, white; Hg, blue; I, green; Li, red [30].
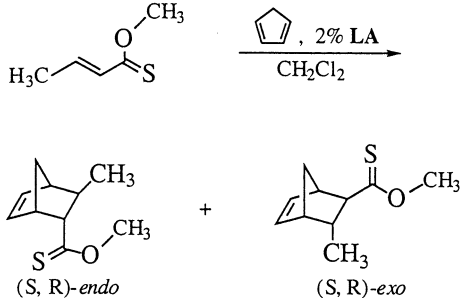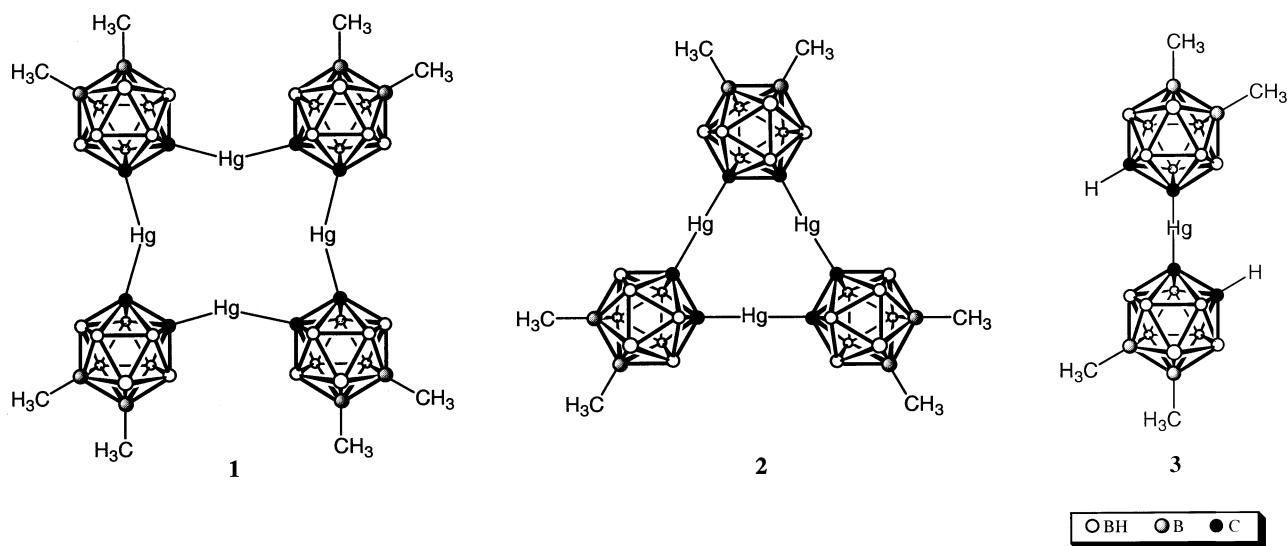

Fig. 18. Representation of octamethyl-[12]mercuracarborand-4 (**1**), hexamethyl-[9]mercuracarborand-3 (**2**), and bis(*closo*-9,12-dimethyl-1,2-carboran-1-yl)mercury (**3**).

Table 1
Diels–Alder reactions of a thionoester and cyclopentadiene

| Lewis acid (LA)	Conditions (°C, days)	Yield[a]% (endo:exo)[b]
1	(0, 2.5)	75 (60:40)
2	(0, 7.5)	83 (99:1)
3	(0, 11)	65 (99:1)
HgI$_2$	(0, 8)	–
Hg(OAc)$_2$	(0, 8)	–
None	(25, 8)	–

[a] Isolated yields.
[b] Determined by 400 MHz ^{1}H-NMR analysis.

shortest amount of time, but the distribution of products showed a disappointing 60:40 endo/exo ratio. The best results were obtained from the use of hexamethyl-[9]mercuracarborand-3 as the catalyst. The isolated yield of products was 83% with an endo/exo ratio of 99:1. A listing of all experimental results is provided in Table 1.

Mercury-199-NMR analyses of the equilibria present in the previous reactions were used to rationalize the results. No shift in the mercury signal could be detected for either hexamethyl-[9]mercuracarborand-3 or bis(closo-9,12-dimethyl-1,2-carboran-1-yl) mercury in the presence of O-methyl-trans-2-butenethioate. This suggests that the coordination of the thionoester by either carboranyl-mercury Lewis acid is relatively weak and facilitates the formation of the kinetic (endo) product through an early product-forming transition state. A stronger coordination of the thionoester sulfur by octamethyl-[12]mercuracarborand-4 was observed by ^{199}Hg-NMR analysis. This strong complexation leads to a mixture of kinetic (endo) and thermodynamic (exo) products which is explained by the catalytic cycle shown in Scheme 4 and a relatively late product-forming transition state [40].

6.2. Electrochemical chloride ion sensor

The parent [9]mercuracarborand-3 was used as a chloride ion sensor electrode in a liquid/polymeric membrane [41]. These polyvinylchloride (PVC)-based ionophore-sensing electrode (ISE) membranes were prepared with only 2% (by weight) [9]mercuracarborand-3, and were doped with various amounts of
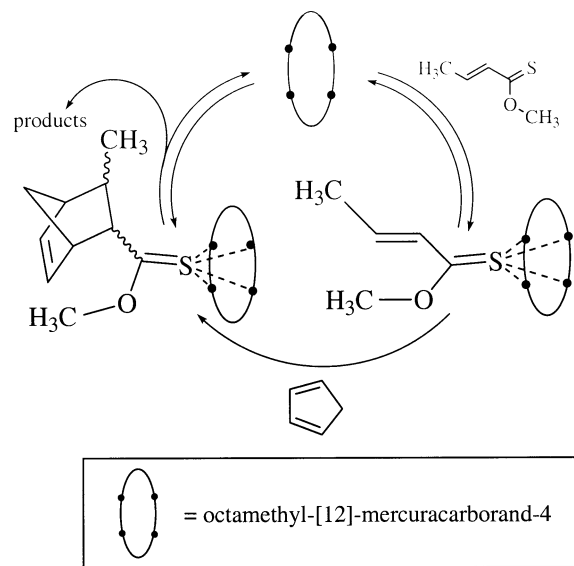

Scheme 4.

lipophilic ionic additives (tridodecylmethylammonium chloride) for potentiometric measurements in a galvanic cell to test chloride ion response. The mercuracarborand trimer showed excellent selectivity for chloride ions over all other anions, with the exceptions of bromide and iodide ions. This is significant because all other known chloride ion sensors bind lipophilic ions, such as perchlorate, salicylate and thiocyanate, as well or better than the target chloride ion [42]. Furthermore, it was determined that [9]mercuracarborand-3 shows no response to cysteine. This suggests that sensors based on [9]mercuracarborand-3 could be used in physiological fluids without interference from proteinaceous cysteine moieties. The mercuracarborand sensor showed no pH response in the range of 2.5–7 pH units, which is also important when considering applications under physiological conditions.

Astoundingly, the [9]mercuracarborand-3-based electrochemical sensor was extremely robust. Reproducible results using this innovative sensor were obtained even after 2 months of usage without signal drop-off. Trimer-based electrode sensors showed fast response times (a few seconds) and short recovery times (less than 1 min).

6.3. Photochemical chloride ion sensor

A highly selective photochemical sensor based on [9]mercuracarborand-3 for the detection of chloride ions was also produced [43]. This sensor was prepared by embedding [9]mercuracarborand-3, a pH-sensitive lipophilic dye, and lipophilic cationic sites in a plasticized polymeric (PVC) membrane. Chloride ion sensing is based on a coextraction process, which is represented in Eq. (1). As the mercuracarborand ionophore (MC3) binds chloride ion, indicator protonation occurs causing

$$MC3 + Cl^- + Ind^- + H^+ + Cat^+ \rightleftharpoons MC3 \cdot Cl^- + IndH + Cat^+$$
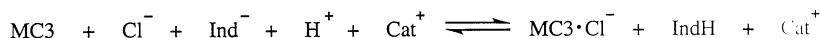
MC3 = [9]mercuracarborand-3
Ind = indicator dye
Cat$^+$ = defined cationic sites

(1)

a large change in membrane absorbance. The doped cationic sites mediate the process, maintaining electroneutrality of the membrane.

As expected from the equation, the sensor does not work well at low pH (~ 3.5 and below) because the equilibrium would be driven far to the right, overloading the acidic indicator and producing a false reading. The optical selectivity sequence for the [9]mercuracarborand-3-based photochemical sensor is much like that of the electrochemical sensor: $I^- > Br^- > Cl^- > SCN^- > salicylate > ClO_4^- \sim NO_3^- > SO_4^-$. Like the electrochemical sensor, this photochemical sensor is highly selective and stable, giving reproducible readings over a wide range of chloride concentration with quick recovery and response times.

7. Summary

Multidentate Lewis acidic host macrocycles comprised of icosahedral carboranes and mercury(II) centers, the so-called tetrameric and trimeric mercuracarborands or "anti-crown" reagents, have proven to be extremely versatile receptors for anion binding. These molecules are synthesized via a kinetic anion template mechanism leading to tetramers while trimers are produced with the absence of this template effect. Substitution of the carborane cages allows mercuracarborands to be tailor-made, in terms of solubility properties, for a variety of applications. Taking advantage of the inherent electron-withdrawing properties of carborane cages, the Lewis acidity of the attached mercury centers has been greatly enhanced. Mercuracarborands are highly stable in solution and in the solid-state and form robust complexes with a large number of electron-rich guests. Supramolecular structures constructed by the self-assembly of mercuracarborand hosts and various guests have resulted in heretofore unseen architectures. Expanding the scope of known coordination geometries of halide ions has been one of the beneficial results of these studies. The availability of guest-free mercuracarborands and the reversible nature of anion complexation have proven ideal for catalysis and ion-sensing. The comprehensive study of mercuracarborands ranging from their synth-

esis, to their host–guest coordination abilities, to their applications has expanded the realm of supramolecular chemistry as demonstrated by this review.

References

[1] C.J. Pedersen, J. Am. Chem. Soc. 89 (1967) 7017.
[2] (a) For reviews of anion complexation, see: (a) D.E. Kaufmann, A. Otten, Angew. Chem. Int. Ed. Engl. 33 (1994) 1832;;
(b) B. Dietrich, Pure Appl. Chem. 65 (1993) 1457.
[3] M.F. Hawthorne, T.E. Berry, P.A. Wegner, J. Am. Chem. Soc. 87 (1965) 4746.
[4] R.N. Grimes, Carboranes, Academic Press, New York, 1970, p. 54.
[5] As an example, see: X. Yang, W. Jiang, C.B. Knobler, M.F. Hawthorne, J. Am. Chem. Soc. 114 (1992) 9719.
[6] As an example, see: W. Jiang, C.B. Knobler, M.D. Mortimer, M.F. Hawthorne, Angew. Chem. Int. Ed. Engl. 34 (1995) 1332.
[7] As an example, see: K. Drechsel, C.S. Lee, E.W. Leung, R.R. Kane, M.F. Hawthorne, Tetrahedron Lett. 35 (1994) 6217.
[8] (a) J. Li, C.F. Logan, M. Jones, Jr., Inorg. Chem. 30 (1990) 4866;
(b) Z. Zheng, W. Jiang, A.A. Zinn, C.B. Knobler, M.F. Hawthorne, Inorg. Chem. 34 (1995) 2095.
[9] X. Yang, C.B. Knobler, M.F. Hawthorne, Angew. Chem. Int. Ed. Engl. 30 (1991) 1507.
[10] X. Yang, C.B. Knobler, M.F. Hawthorne, J. Am. Chem. Soc. 114 (1992) 380.
[11] X. Yang, S.E. Johnson, S.I. Khan, M.F. Hawthorne, Angew. Chem. Int. Ed. Engl. 31 (1992) 893.
[12] M.D.S. Healy, A.J. Rest, Adv. Inorg. Chem. Radiochem. 21 (1978) 1.
[13] X. Yang, Z. Zheng, C.B. Knobler, M.F. Hawthorne, J. Am. Chem. Soc. 115 (1993) 193.

[14] Z. Zheng, M. Diaz, C.B. Knobler, M.F. Hawthorne, J. Am. Chem. Soc. 117 (1995) 12338.

[15] F.A. Gomez, M.F. Hawthorne, J. Org. Chem. 57 (1992) 1384.

[16] L.I. Zakharkin, I.V. Pisareva, Izv. Akad. Nauk. SSSR Ser. Khim. (1977) 1747.

[17] V.I. Bregadze, V.Ts. Kampel, N.N. Godovikov, J. Organomet. Chem. 112 (1976) 249.

[18] L.I. Zakharkin, I.V. Pisareva, Izv. Akad. Nauk. SSSR Ser. Khim. (1979) 1750.

[19] M.F. Hawthorne, P.A. Wegner, J. Am. Chem. Soc. 90 (1968) 896.

[20] Z. Zheng, X. Yang, C.B. Knobler, M.F. Hawthorne, J. Am. Chem. Soc. 115 (1993) 5320.

[21] Z. Zheng, C.B. Knobler, M.F. Hawthorne, J. Am. Chem. Soc. 117 (1995) 5105.

[22] X. Yang, C.B. Knobler, M.F. Hawthorne, J. Am. Chem. Soc. 115 (1993) 4904.

[23] Z. Zheng, C.B. Knobler, M.D. Mortimer, G. Kong, M.F. Hawthorne, Inorg. Chem. 35 (1996) 1235.

[24] A.A. Zinn, Z. Zheng, C.B. Knobler, M.F. Hawthorne, J. Am. Chem. Soc. 118 (1996) 70.

[25] M.A. Sen, N.K. Wilson, P.D. Ellis, J.D. Odom, J. Magn. Reson. 19 (1975) 323.

[26] R.J. Goodfellow, in: J. Mason (Ed.), Multinuclear NMR, Plenum, New York, 1987, p. 563.

[27] X. Yang, C.B. Knobler, Z. Zheng, M.F. Hawthorne, J. Am. Chem. Soc. 116 (1994) 7142.

[28] M.F. Hawthorne, X. Yang, Z. Zheng, Pure Appl. Chem. 66 (1994) 245.

[29] M.F. Hawthorne, Z. Zheng, Acc. Chem. Res. 30 (1997) 267.

[30] H. Lee, C.B. Knobler, M.F. Hawthorne, Angew. Chem. Int. Ed. Engl. 40 (2001) 2124.

[31] A.A. Zinn, C.B. Knobler, D.E. Harwell, M.F. Hawthorne, Inorg. Chem. 38 (1999) 2227.

[32] H. Lee, C.B. Knobler, M.F. Hawthorne, Angew. Chem. Int. Ed. Engl. 40 (2001) 3058.

[33] S. Suzuki, P.G. Green, R.E. Bumgarner, S. Dasgupta, W.A. Goddard, III, G.A. Blake, Science 257 (1992) 942.

[34] K.S. Kim, J.Y. Lee, H.S. Choi, J. Kim, J.H. Jang, Chem. Phys. Lett. 265 (1997) 497.

[35] H. Lee, M. Diaz, C.B. Knobler, M.F. Hawthorne, Angew. Chem. Int. Ed. Engl. 39 (2000) 776.

[36] H. Lee, C.B. Knobler, M.F. Hawthorne, J. Am. Chem. Soc. 123 (2001) 8543.

[37] A.J. Canty, G.B. Deacon, Inorg. Chim. Acta 45 (1980) L225.

[38] L. Pauling, The Nature of the Chemical Bond, 3rd ed., Cornell University Press, Ithaca, NY, 1960, p. 260.

[39] O.M. Yaghi, H. Li, C. Davis, D. Richardson, T.L. Groy, Acc. Chem. Res. 31 (1998) 474.

[40] H. Lee, M. Diaz, M.F. Hawthorne, Tetrahedron Lett. 40 (1999) 7651.

[41] I.H.A. Badr, M. Diaz, M.F. Hawthorne, L.G. Bachas, Anal. Chem. 71 (1999) 1371.

[42] (a) U. Oesch, D. Ammann, W. Simon, Clin. Chem. 32 (1986) 1448;
(b) K. Hartman, S. Luterotti, H.F. Osswald, M. Oehme, P.C. Meier, D. Ammann, W. Simon, Mikrochim. Acta (Wien) (II) (1978) 235;
(c) S. Ozawa, H. Miyagi, Y. Shibata, N. Oki, T. Kunitake, W.E. Teller, Anal. Chem. 68 (1996) 4149;
(d) S. Oka, Y. Shibazaki, S. Tahara, Anal. Chem. 53 (1981) 588;
(e) F. Hofmeister, Arch. Exp. Pathol. Pharmakol. 24 (1888) 247;
(f) R. Lewandowski, T. Sokalski, A. Hulanicki, Clin. Chem. 35 (1989) 2146;
(g) R.J. Elin, E.A. Robertson, E. Johnson, Clin. Chem. 27 (1981) 778;
(h) M. Panteghini, R. Bonora, A. Malchiodi, M. Calarco, Clin. Biochem. 19 (1986) 20.

[43] I.H.A. Badr, R.D. Johnson, M. Diaz, M.F. Hawthorne, L.G. Bachas, Anal. Chem. 72 (2000) 4249.