

Host-Guest Complexation. 51. Cyanospherands, a New Type of Salt Binder¹

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Abstract: The syntheses and properties are described for the cyanospherands, a new type of complexing agent for salts. Eight, ten, and twelve 4-methylcyanobenzenes are incorporated into macrocycles by attachment to one another at their 2,6-positions to provide arrays of cyano groups that are preorganized to converge on enforced cavities. A crystal structure of $(4\text{-CH}_3\text{-C}_6\text{H}_2\text{CN})_8\cdot 2\text{H}_2\text{O}$ (octacyanospherand dihydrate) shows that this host contains an enforced $(u-d)_4$ (*u* means up, and *d*, down) arrangement of eight cyano groups that define an unoccupied square-antiprismatic cavity, with one water loosely hydrogen-bonding two transannularly located cyano groups on each face of the macrocoring. This host belongs to an approximate D_{4d} point group. The diameter of the roughly spherical cavity is about 3.2 Å. A crystal structure of $(4\text{-CH}_3\text{C}_6\text{H}_2\text{CN})_8\cdot 2\text{KBr}\cdot 4\text{C}_5\text{H}_5\text{N}$ provides a similar, but slightly smaller, unoccupied cavity for the host, with each K^+ ligating the four CN groups in a perching arrangement on each face of the macrocycle. Four pyridines act as bridges between the two potassium ions associated with different hosts to give anions and cations stacked in parallel axes. Each bromide ion is in a large cavity lined with four methyls and four aryl hydrogens of the cyanospheraplex in a stacked arrangement. The approximate symmetry of the cyanospheraplex is D_{4d} . The ^{13}C and ^1H NMR spectra of the octacyanospherand and its complexes indicate that the host's solution structures resemble the crystal structures. A CDCl_3 solution of octacyanospherand dissolved 1 equiv of solid $(\text{CH}_3)_4\text{NBr}$. The average aggregation numbers (N_{av}) in CHCl_3 at 46 °C for the octacyanospherand-binding KBr and CsBr at 3 mM concentration (vapor pressure osmometry) are 1.0 ± 0.1 . Host solutions (*H*) in CDCl_3 at 1 mM concentration were used to extract from equal volumes of D_2O picrate salts (*G*) at increasing concentrations at 25 °C until the host in CDCl_3 was saturated with guest (*G**). Saturation of octacyanospherand occurred at a 2:1 ratio of $[\text{G}^*]/[\text{H}]$ in the CDCl_3 phase with $[\text{G}]/[\text{H}] = 6.0, 5.0, 10.0,$ and 15.0 in the D_2O layer for $\text{Na}^+, \text{K}^+, \text{Cs}^+,$ and NH_4^+ , respectively. At $[\text{H}] = [\text{G}] = 1 \text{ mM}$, only 1:1 or lower ratios of $[\text{G}^*]/[\text{H}]$ were observed. By our standard salt extraction method from D_2O into CDCl_3 at 25 °C, octacyanospherand (**1**) was found to bind $\text{Li}^+, \text{Na}^+, \text{K}^+, \text{Rb}^+, \text{Cs}^+, \text{NH}_4^+, \text{CH}_3\text{NH}_3^+,$ and $(\text{CH}_3)_3\text{CNH}_3^+$ picrates with $-\Delta G^\circ$ values (kcal mol^{-1}) that ranged from 9.9 to 14.1 and peaked with K^+ . Thus four preorganized $\text{ArC}\equiv\text{N}$ groups acting cooperatively provide strong and relatively indiscriminate binding to these ions. The open-chain counterpart of octacyanospherand gave $-\Delta G^\circ$ values of $<6 \text{ kcal mol}^{-1}$, showing the importance of preorganization of ligating groups in the octacyanospherand. Solutions of decacyanospherand (**2**) and dodecacyanospherand (**3**) were subjected to similar structural and binding studies.

This paper reports the synthesis, crystal structure, and binding properties of octacyanospherand (**1**) and the syntheses and binding properties of decacyanospherand (**2**) and dodecacyanospherand (**3**). Molecular models (CPK) of **1** can only be assembled in a

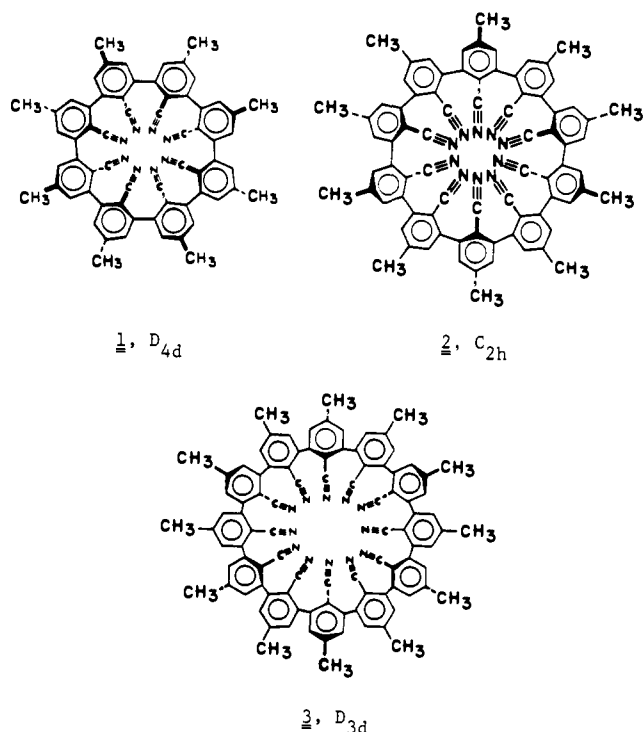


Table I. Geometric Parameters for Crystal Structures of Octacyanospherand (**1**)

		1·2H ₂ O	1·2KBr·4py
Ar-Ar dihedral angle,	av	79	68
	deg	85, 70 ^a	
max deviatn of		0.02	0.015
benzene C's from Ar			
plane, Å			
tilt angle of Ar's from	av	47	38
best plane, ^b Å	range	39, 54	
av distance (Å)		0.10 (4)	0.09
between Ar plane and		0.05 (4)	
	(bent in)	0.26 (4)	0.22
	(bent out)	0.06 (4)	
Ar-C-N bond angle,	av	176.2	177
	deg	173.9,	
		178.5	
bond distance	av	1.47	1.45
of Ar-CN, Å	range	1.45, 1.49	
bond distance of	av	1.13	1.13
C≡N, Å	range	1.12, 1.14	
av distance (Å)		3.66 (4.01,	3.31
	N in the same face	3.31)	
		4.78 (4.44,	4.20
between N and	N of opposite face	4.85, 5.04)	

^aTwo values are listed for 1·2H₂O because it is less symmetric than 1·2KBr·4 py. ^bDefined by carbons of Ar-Ar linkages. ^cBent outward from plane of attached aryl.

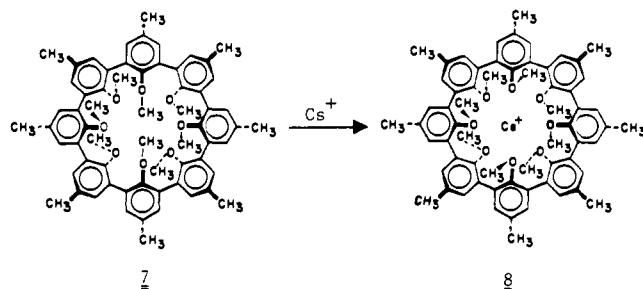
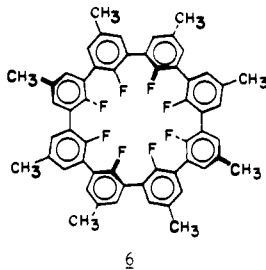
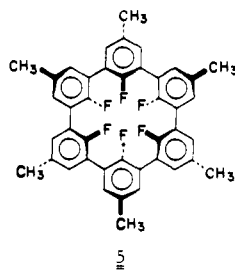
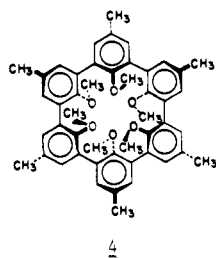
$(u-d)_4$ (*u* means up, *d*, down, and *m*, middle) enforced conformation, which places the positive carbons of the eight $\text{C}\equiv\text{N}$ groups in a square-antiprismatic arrangement around a nearly spherical cavity of about 3.2-Å diameter. The radius of the cavity is defined by the N-centroid distance minus 1.8 Å, the van der Waals radius of N in $\text{Ar}-\text{C}\equiv\text{N}$. From each face of the macrocoring protrude four nitrogen sp orbitals whose axes converge on a point above the square-planar nitrogens. The group dipole moment of $\text{C}_6\text{H}_5\text{C}\equiv\text{N}$ is 4.39 D in the gas phase.^{2b} Thus it

(1) We gratefully acknowledge support for this research from the Division of Basic Sciences of the Department of Energy, Grant DE 88-ER13892.

seemed probable that the nitrogens of **1** would bind metal ions in a perching arrangement at each face of the macrocyclic ring and possible that the cavity would capsularly bind anions that would mildly ligate the eight carbons of the cavity. These two kinds of binding should enhance each other to make **1** a good salt-complexing agent.

Models of **2** and **3** indicated their units to be much more conformationally mobile than those of **1**. In one of its conformations, **2** contains four rectangularly arranged, coplanar nitrogens with the axes of their sp orbitals converging on a point in the center of a cavity (C_{2h} symmetry). In one conformation of **3**, six hexagonally arranged, coplanar nitrogens have their sp orbitals converging on a point in the center of a larger cavity (D_{3d} symmetry). Of these three hosts, only **1** is preorganized to potentially exhibit complementary anionophoric and cationophoric properties, while **2** and **3** are only partially preorganized to act as cationophores.

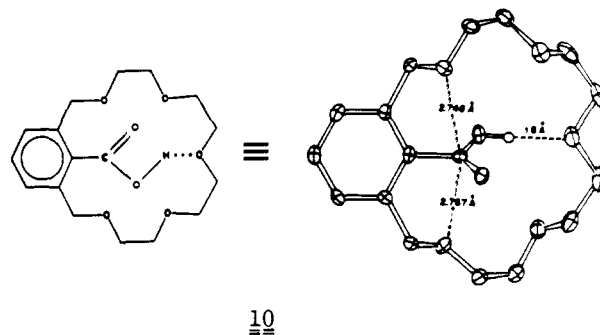
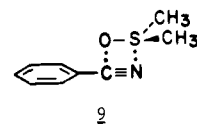
Potential cationophores based on metacyclophane ring systems are exemplified by **4**,^{2a} **5**, **6**,³ and **7**.⁴ The crystal structures of



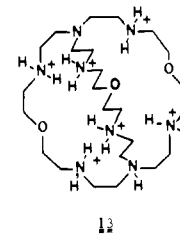
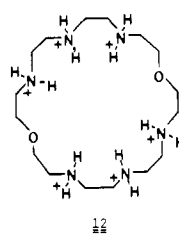
4, **5**, and **7** show the presence of highly preorganized cavities. Spherand **4** is a very strong binder of Li^+ and Na^+ , **5** and **6** have no binding properties, and **7** partially reorganizes to strongly bind Cs^+ to give **8**, whose crystal structure is also known.³ Although highly preorganized for binding, **5** and **6** show no capacity to act as hosts.³ Thus, the metacyclophane ring system serves as a good support for convergent functional groups to act cooperatively in complexation, provided the groups in question possess some intrinsic propensity for binding.

Several properties of nitriles suggested they might act as salt binders. It has been postulated that $CH_3C\equiv N$ self-associates in

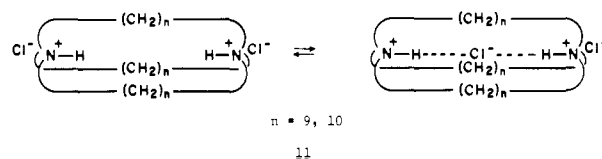
the gas⁵ and solution⁶ phases.⁷ A cryoscopic study of nitriles and dimethyl sulfoxide indicates they associate, probably forming complexes such as **9**.⁸ Abnormally short $O\cdots CO_2H$ distances (2.75 and 2.77 Å) in the crystal structure, **10**, provide evidence for the intramolecular association of carbon carrying a partial positive charge binding unshared electron pairs on oxygen.⁹



In comparison to cationophores,² few kinds of anionophores are known. In 1968, Park and Simmons¹⁰ reported that protonated "in-in" catapinands (**11**) incorporate halogen ions into their



positively charged cavities. Since 1976, Lehn et al.¹¹ have developed cyclic and polycyclic systems (such as **12** and **13**) containing multiple partially preorganized NH groups as highly selective anionophores. Since 1985, Wuest et al.,¹² Newcomb et al.,¹³ and Katz¹⁴ have reported that compounds containing respectively, covalently bound multiple mercury, tin, and boron atoms show binding of the smaller anions.



This paper is organized as follows. The syntheses of the three cyanospherands and of open-chain model systems are described in the first section. The second section reports the crystal structures of octacyanospherand ($1 \cdot 2H_2O$) and its complex, **1**.

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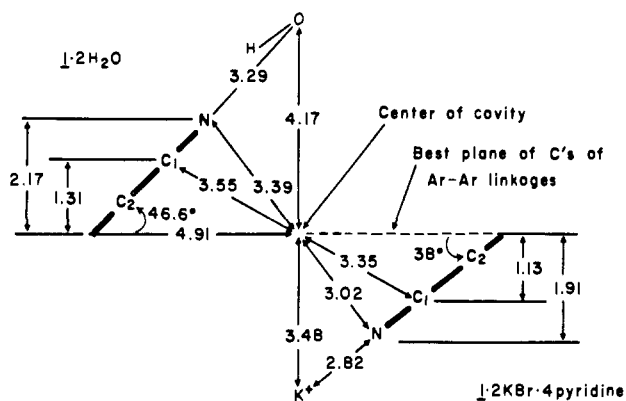
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Table II. Chemical Shift Changes in the ^{13}C NMR Spectra of Octacyanospherand (**1**) at 0.011 M with Changes in Guest

run no.	solvent	guest	[G]:[H]	$\sigma_{\text{complexed}} - \delta_{\text{free}}$					
				C ₁	C ₂	C ₃	C ₄	C ₅	C ₆
1	(CD ₃) ₂ SO	NaBr	40:1	1.49	-2.32	2.64	1.90	0.12	0.24
2	(CD ₃) ₂ SO	CsBr	20:1	-0.03	-1.47	0.98	0.49	-0.14	-0.21
3	(CD ₃) ₂ SO	Me ₄ NPF ₆	10:1	-0.04	-0.28	-0.05	-0.13	-0.16	-0.21
4	(CD ₃) ₂ SO	Bu ₄ NI	10:1	-0.46	-0.25	-0.54	-0.46	-0.36	-0.38
5	(CD ₃) ₂ SO	Bu ₄ NI	30:1	-0.40	-0.30	-0.43	-0.46	-0.36	-0.30
6	CDCl ₃	Me ₄ NBr	0.63:1	-0.09	-0.09	-0.19	-0.12	-0.11	0.23
7	CDCl ₃	Et ₄ NBr	3:1	0.24	-0.07	0.00	-0.18	-0.17	0.04

**Figure 1.** Cavity dimensions defined by distances (Å) of C—C≡N atoms from centers of 1·2H₂O (upper left quadrant) and 1·2KBr·4py (lower right quadrant).

2KBr·4py (py = pyridine). The third section deals with the solution ^1H NMR spectra and conformations of the uncomplexed hosts. The fourth section treats the spectral properties and conformation of the octacyanospheraplexes, while the fifth, those of the decacyanospheraplexes and dodecacyanospheraplexes. The sixth section describes the cation-binding properties of the hosts.

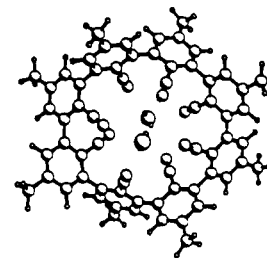
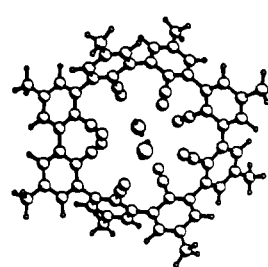
Results and Discussion

Syntheses. Hosts **1–3** were synthesized as outlined in Scheme I. Bromination of *p*-toluidine gave **14** (~100%), which when subjected to the Sandmeyer reaction¹⁵ provided the key starting material **15** (56%) for the incremental syntheses. Monolithiation of **15** followed by oxidative coupling of the organometallic formed with 1.2 equiv of anhydrous CuCl₂ at -78 °C in THF gave **16** (53%). A similar sequence applied to **16** led to **17** (50%). Other oxidizing reagents (e.g., Cu(OSO₂CF₃)₂ and Fe(acac)₃) gave inferior yields. Linear octamer **18** was obtained (18%) by the same lithiation–CuCl₂ oxidation sequence used for preparing **16** and **17**. The lower yield of **18** as compared to those for **16** and **17** appeared from the byproducts to arise from statistical mono-, di-, and nonmetalation of **17**. Monometalation of **15** and **16** seemed to predominate, as expected.

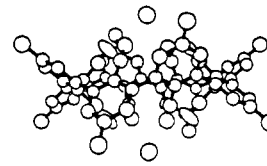
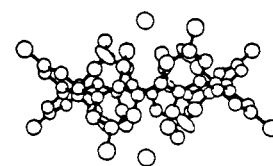
The oligomeric ring-closure yields were maximized. Dimeric compound **16** was lithiated with (CH₃)₃CLi (4.4 equiv in pentane) at -78 °C in THF, and the resulting dilithiate was cannulated into a large volume of toluene (reflux temperature) containing 4.4 equiv of Fe(acac)₄ under argon over a period of 30 min. The mixture of cycles and reduced open-chain materials was purified, making use of the salt-binding properties of **1–3**. The reaction mixture was washed with dilute acid and then water, and the residue left after evaporation was dissolved in CH₃CN. This material was submitted to reverse-phase flash chromatography. The octacyanospherand (**1**) was eluted with CH₃CN/CH₃OH/2

M NaBr, 2:1:1), and the mixture of **2** and **3**, with CH₃CN/CH₃OH/1 M KCl, 5:4:1. Hosts **2** and **3** were separated by fractional crystallization and further chromatography.

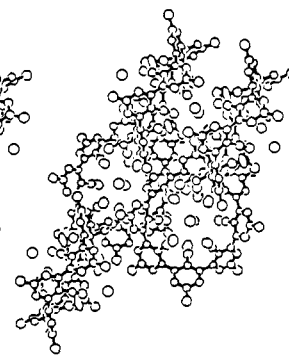
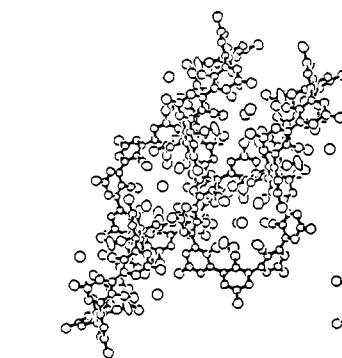
Crystal Structures. Crystals of octacyanospherand dihydrate (1·2H₂O) were found suitable for crystal structure determination (*R* = 0.10). Stereo face and side views are given in **18** and **19**,



18



19



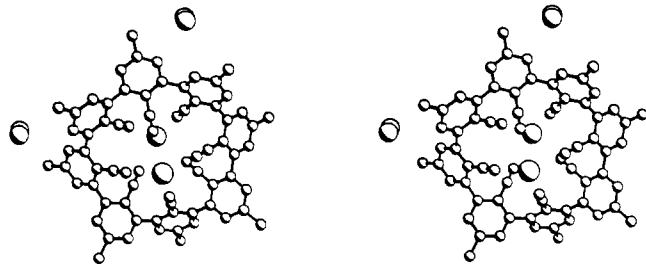
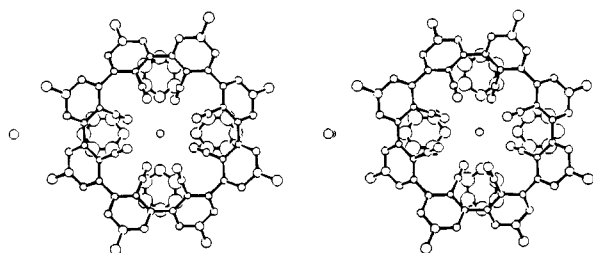
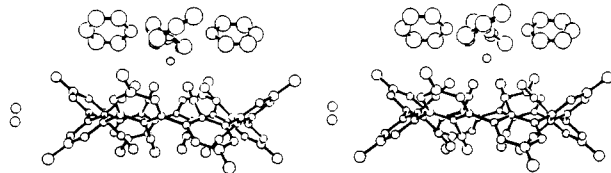
20

respectively, while **20** provides a drawing of the crystal packing. As expected from CPK molecular model examination, **18** and **19** show that the eight cyano groups converge on one another in a (u-d)₄ conformation providing the molecule with approximate *D*_{4d} symmetry. An empty, nearly spherical cavity of about 3.2-Å diameter is defined by the eight C—C≡N groups in a square-antiprismatic arrangement. A water molecule perches on each face of the cyanospherand, very loosely hydrogen bonded to two nitrogens, in **18** located at about 1 and 7 o'clock on the top face

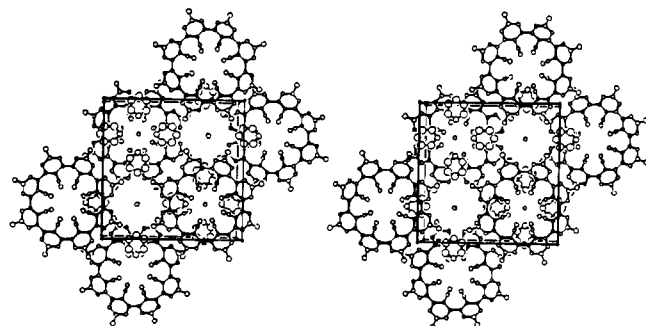
(15) See ref 2b for examples.

and at about 11 and 5 o'clock on the bottom face. Although all O—H...N arrangements are nearly linear, the O to N distance (3.3 Å) is longer than most hydrogen bonds. Table I records the relevant bond lengths and angles.

After many trials, crystals of suitable quality of complex 1·2KBr·4py were obtained for X-ray crystal determination ($R = 0.17$, bromide ions are disordered). In face stereoview **21** of

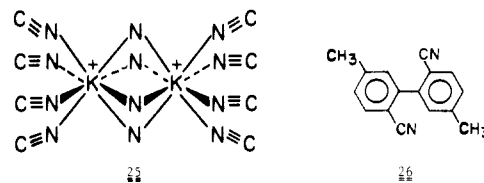
**21****22****23**

1·2KBr·4py, the pyridines are omitted; in face stereoview **22**, one KBr is omitted; in side stereoview **23**, one KBr is omitted, and the disorder of the bromide ion is visible. A face stereoview of the crystal-packing structure is shown in **24**. As in **18**, the host

**24**

of the complex possesses approximate D_{4d} symmetry and contains an *empty, nearly spherical* cavity of about 2.4-Å diameter outlined by the eight C—C≡N groups in a square-antiprismatic (u-d)₄ arrangement. A K⁺ perches on each face of the macrocycle ligated by the sp orbitals of four convergent cyano groups (see **21**). Each K⁺ is also ligated by the nitrogens of four pyridines (see **22**) arranged like a four-bladed propeller above and below each face

of the macrocycle (see **23**). Each pyridyl nitrogen ligates two K⁺ ions, providing four nitrogen bridges between each K⁺ (see diagram **25**) to form a stacked, polymeric complex. The bromide ions are



arranged around the equator of the macrocycle (see **21–23**). They appear to be loosely contained in channels, lying close to four methyls and two aryl hydrogens involving two different macrocycles. The anion disorder could be due to the poor fit of the bromide in the channel. Thus K⁺ and Br[−] ions each lie on different but parallel channels, which are 9.3 Å apart (see **24**). Table I contains selected angles and distances. *The expectation that bromide ions would occupy the cavity of octacyanospherand (1) was not fulfilled.*

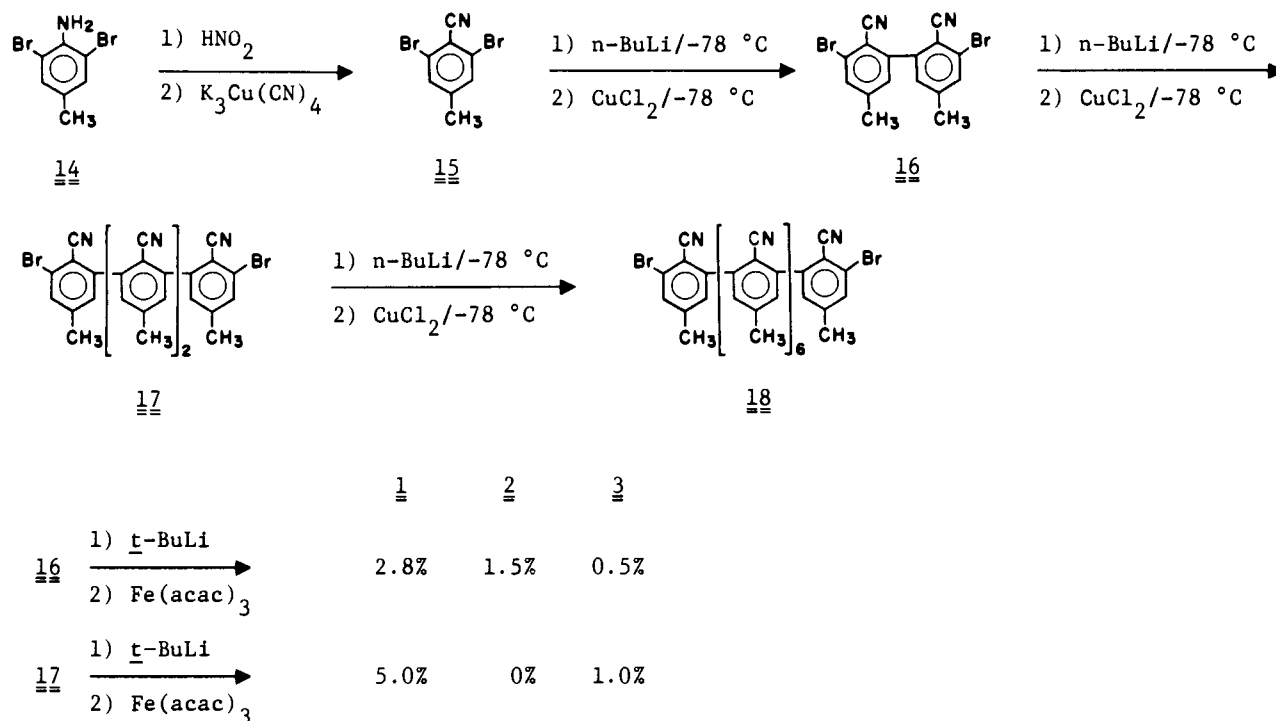
A comparison of the conformations of the 24-membered cyclic hosts, octafluorocavitand (**6**),⁴ octamethoxyspherand (**7**),³ and octacyanospherand (**1**) is instructive. The nonbinding octafluoro compound **6** exists in the conformation (u-m-d-m)₂ with D_{2d} symmetry (evidence from ¹⁹F NMR), which minimizes its cavity size. The octamethoxy host **7** has the square-antiprismatic oxygen arrangement (u-d)₄ with its methoxy methyls at 12 and 6 o'clock turned inward to partially fill its cavity and provide C_{2v} symmetry. These two methyl groups turn outward in its Cs⁺ complex **8** to provide approximate D_{4d} symmetry (crystallographic mirror). The octacyanospherand host in 1·2H₂O and in 1·2KBr·4py possesses the same conformation and symmetry as **8** ((u-d)₄, D_{4d}). We conclude that, for the maintenance of conformational stability of 24-membered carbocycles of this type, CN > OCH₃ > F as inward-oriented substituents.

The effects of complexation of **1** on its geometric parameters are apparent from comparisons in Table I. The Ar—Ar dihedral angles for 1·2H₂O averaged 79° but decreased to 68° in 1·2KBr·4py. The corresponding o,o'-NCAr—ArCN dihedral angle in the crystal structure for model compound **26** is 127°, which reflects the tendency of the two Ar—C≡N dipoles to compensate each other.¹⁶ These values suggest that incorporation of eight *p*-CH₃C₆H₂CN units into a macrocycle involves a considerable amount of strain. It also seems likely that this dihedral angle in free **1** is larger than in 1·2H₂O, so that, with respect to the dihedral angle, **26** > **1** > 1·2H₂O > 1·2KBr·4py. Comparison of free spherand **7** with its spherplex **8** (7·Cs⁺) shows that the average dihedral angle of 79° (62–90°) decreases to 65° (58–74°) upon complexation to form **8**. The benzene rings in octacyanospherand (**1**) and its complex are nearly planar, as are those in spherand **7** and its complex,³ the maximum deviation from planarity in all four structures being <0.02 Å.

The average and range of the tilt angle of the aryls from the best plane (defined by the carbons of the Ar—Ar linkages) provide a measure of the rigidity of the macrocycle and convergence of the cyano groups, respectively (Table I). In 1·2H₂O, the average angle is 47° and the range is 39–54°, whereas in 1·2KBr·4py, the angle is 38°. Thus the cyano groups converge much more when ligating K⁺. Similarly, **7** has an average tilt angle of 43° (18–61°). Spherplex 7·Cs⁺ (**8**) has an average tilt angle of 36° (27–42°) similar to the cyanospherplex, where all tilt angles are equal by symmetry. Models of 7·Cs⁺ suggest the host cavity is a little too large for Cs⁺ and that the Cs⁺ "rattles around" to a limited extent.³

The incorporation of cyano groups into the macrocyclic host has interesting consequences. In 1·2H₂O and 1·2KBr·4py, the C and N of the cyano groups are bent slightly out of the planes of their attached aryls. In the former, four of the C's are bent outward away from the cavity by 0.1 Å, while four are nearly in the ring plane. Four of the N's are bent outward by 0.26 Å, and the other four are nearly in the ring plane. In the latter complex, all of

Scheme 1



the C and N atoms are bent outward, the C's by 0.08 Å and the N's by 0.22 Å. These deformations of the C—C≡N from linearity are also evident in the bond angles of 176° average (174°, 178°) for 1·H₂O and 177° for 1·2KBr·4py, respectively. The Ar—CN bond distance in 1·2H₂O averages to 1.47 Å (1.45, 1.49 Å) while that in 1·2KBr·4py is 1.45 Å. The average C≡N bond distance in 1·H₂O of 1.13 Å (1.12, 1.14 Å) is about the same as that in 1·2KBr·4py (1.13 Å). The average N to N distances for the cyanospherand and its complex are 3.66 and 3.31 Å, respectively, for alternate cyano groups (located on the same face) and 4.78 and 4.20 Å for adjacent cyano groups (located on opposite faces).

The cavity dimensions in the crystal structure 1·2H₂O and 1·2KBr·4py are illustrated in Figure 1. The most important distances are those of the cyano atoms from the center of the cavity. Notice that in 1·2H₂O (upper left quadrant of Figure 1) N of C≡N is an average of 3.39 Å (3.31, 3.47) from the center, less than that of C₁ at 3.55 Å (3.53, 3.57). In 1·2KBr·4py (lower right quadrant), the N distance is 3.02 Å, less than the C₁ distance of 3.35 Å. At these distances, the repulsion of the partial negative charges on the nitrogens for a cavity-bound anion should outweigh attractions of partial positive charges on C₁ of the cyano group for a cavity-bound anion. If the radius of the cylindrical π-electrons of the C≡N group is taken as 1.8 Å,¹⁷ the diameter of the cavity of 1·2H₂O becomes 3.2 Å, and that of 1·2KBr·4pyridine, 2.4 Å. It is clear that the nitrogen ligation of K⁺ shrinks the diameter of the cavity and that any of the alkali-metal ions would to varying degrees. If the van der Waals radius of the sp orbital of the cyano nitrogens is counted as 1.50 Å,¹⁸ the radius of K⁺ becomes 1.32 Å, comparable to its standard van der Waals radius of 1.33 Å.¹⁹

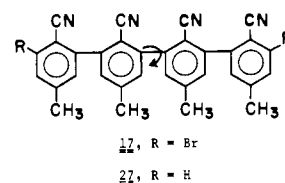
The diameter of Cl⁻ is 3.62 Å, that of Br⁻ is 3.90 Å, and that of I⁻ is 4.40 Å.¹⁹ These diameters are substantially higher than those of the cavities of either 1·2H₂O or 1·2KBr·4py. By increasing the tilt angle of the ArC≡N groups from the best plane of the macroring (defined by carbons of Ar—Ar linkages) to about 60°

and retaining *D*_{4d} symmetry, the cavity diameter becomes 4.9 Å, and the N to the center distance becomes slightly greater than the C₁ distance of 4.3 Å to the center. Thus the greatest change of finding Br⁻ or I⁻ in the cavity of 1 would have to involve a counterion of the highest possible diameter so that the ligating nitrogens were not drawn together as with K⁺ or H₂O. Thus salts such as (CH₃)₄NBr or (*n*-Bu)₄NI would have the best chance of having their anions capsularly complexed by 1.

Spectra (¹H NMR) and Conformations of the Cyanospherands. The ¹H NMR spectrum of octacyanospherand (1) in CD₂Cl₂, CDCl₃, CD₃CN, (CD₃)₂SO, and (CD₃)₂NCDO exhibits only two sharp singlets, corresponding to the 24 CH₃ and 16 ArH₂ protons, respectively. In CDCl₃, these are found at δ 2.50 and 7.31, respectively. The spectrum in CD₂Cl₂ did not change when the solution was cooled to -80 °C. The simplicity of this spectrum is compatible with the *D*_{4d} symmetry for 1 observed in the crystal structure work. Thus 1 possesses the (u-d)₄ conformation of the aryl groups both in the crystalline and solution states.

The ¹H NMR spectrum of the 30-membered decacyanospherand (2) shows two sharp singlets in CDCl₃ at δ 2.62 and 7.37, corresponding to the 30 CH₃ and 20 ArH₂ protons, respectively. The multiplicity of these peaks did not change when CD₂Cl₂, (CD₃)₂NCDO, and C₆D₅NO₂ were used as solvents or when the temperature was lowered to -80 °C in CD₂Cl₂. This spectrum is consistent with the molecule having the (u-d)₅ conformation with *D*_{5d} symmetry in its noncomplexed state.

The ¹H NMR spectrum of dodecacyanospherand (3) contains two broad singlets for the methyl and aryl protons in CDCl₃ at δ 2.54 and 7.44, respectively. As the temperature is decreased, the aryl protons go to a broad multiplet, but the methyl protons remain a broad singlet. Probably at 25 °C, the rather flexible system (CPK model examination) exists as an averaging mixture of conformers. The degree of hindrance to rotation about the aryl-aryl bonds in the linear tetramer 17 was examined in CD₂Cl₂



(17) Reference 2b, pp 209–212.

(18) (a) Stern, K. H.; Amis, E. S. *Chem. Rev.* **1959**, *59*, 1–64. (b) Considine, D. M.; Considine, G. D., Eds. *Encyclopedia of Chemistry*, 4th ed.; Van Nostrand Reinhold: New York, 1984; p 216.(19) Waser, J.; Trueblood, K. N.; Knobler, C. M. *Chem. ONE*; McGraw Hill Book Co.: New York, 1976; p 283.by a variable-temperature ¹H NMR (200-MHz) experiment.²⁰

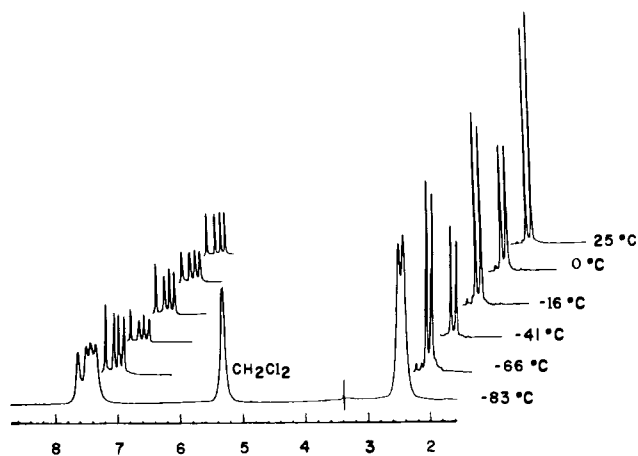


Figure 2. Dynamic ^1H NMR spectra of **17** in CD_2Cl_2 .

Figure 2 provides the results. The spectra suggest that hindered rotation on the ^1H NMR time scale begins to appear below -41°C . In **3** the cyano groups probably rotate quite freely through the 36-membered macroring at 25°C to provide a mixture of equilibrating conformers, resulting in broad singlets.

Spectral Properties and Conformation of Octacyanospheraplexes.

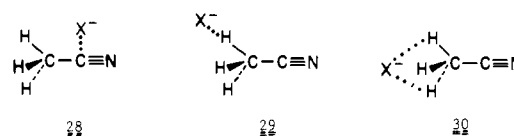
A CDCl_3 solution of host **1** dissolved 1 equiv of solid $(\text{CH}_3)_4\text{NBr}$, whereas only trace amounts of the same salt dissolved in the absence of host **1**, even when the CDCl_3 solvent was saturated with D_2O . The peak corresponding to the CH_3 groups of the guest moved upfield to δ 2.79 in the dry solution. When enough D_2O was added to the spectra solution of the 1:1 complex to saturate it with D_2O , the signal for the CH_3 groups of the guest moved to δ 3.16. The signals for the host at δ 2.50 ($\text{CH}_3\text{-Ar}$) and 7.31 (C_6H_2) remain unchanged before and after dissolution of the salt and addition of the water. These results suggest that, in the complex of **1**· $(\text{CH}_3)_4\text{NBr}$ in dry CDCl_3 , the methyl groups of the guest perch on the sp orbitals of four syn nitrogens much like the K^+ ion in the crystal structure of **1**· $2\text{KBr}\cdot 4\text{py}$. Since these orbitals define the shielding region of the cyano groups, the methyl protons move upfield. When water is added, it displaces the $(\text{CH}_3)_4\text{N}^+$ from the nitrogens by hydrogen bonding the sp orbitals as in the crystal structure of **1**· $2\text{H}_2\text{O}$. When complexes with a wide variety of salts ($(\text{CH}_3)_4\text{NBr}$, KBr , CsBr , NaN_3 , NaClO_4 , and $(n\text{-Bu})_4\text{NBH}_4$), no significant changes in chemical shifts of **1** were observed. The chemical shift of the BH_4^- protons of $(n\text{-Bu})_4\text{NBH}_4$ were also determined as a function of the concentration of **1** in CDCl_3 . No changes were observed for the signal even at a [guest]/[host] ratio of 10. Had BH_4^- been capsularly complexed, large shifts in the proton signals should have been observed.

Unlike the ^1H NMR spectrum of complexed octacyanospherand (**1**), the ^{13}C NMR spectra in $(\text{CD}_3)_2\text{SO}$ and CDCl_3 of **1** do change with changes in the guest. Table II records the values of δ complexed - δ free for the six kinds of carbons of the host. These carbons were assigned by addition of substituent constants to the standard shift of benzene (128.5 ppm) by the standard method.²¹ Runs 1 and 2 show that generally $\text{NaBr} > \text{CsBr} > \text{R}_4\text{NX}$ in ability to induce significant chemical shift changes in the host ($\Delta\delta$ range from +2.64 to -2.32 ppm) particularly at C-1, C-2, C-3, and C-4. These are the smallest cations of the group and probably caused the greatest change in geometry of the host through their ligation by the $(\text{CN})_4$ assemblies. Runs 3-7 involving different quaternary ammonium cations gave $\Delta\delta$ values that ranged from 0.00 to -0.54 , the largest $\Delta\delta$ values (-0.54 to -0.25) being associated with Bu_4NI (runs 4 and 5). In these runs, the [G]/[H] ratio was changed from 10:1 to 30:1 with significant changes in $\Delta\delta$. Runs 3 and 4 made in $(\text{CD}_3)_2\text{SO}$ differ only in that, in run 3, Me_4NPF_6 was the added salt and, in run 4, Bu_4NI was the added salt. In **3**, $\Delta\delta$

varied from -0.04 to -0.28 while in **4**, $\Delta\delta$ varied from -0.25 to -0.54 . Since I^- in models is small enough to enter the cavity but PF_6^- is not, it is conceivable that this $\Delta\delta$ change is due to capsular binding of I^- . Runs 6 and 7 made in CDCl_3 involved Me_4NBr and Et_4NBr and gave different patterns of $\Delta\delta$ values, but too many parameters are changed to provide any conclusion. These results taken as a whole suggest that cation binding to **1** is more important than anion binding but that the latter cannot be ruled out.

The infrared stretching frequency of the $\text{C}\equiv\text{N}$ band of **1** in CDCl_3 remained at 2247 cm^{-1} upon addition of 1 equiv of either Me_4NBr or NaN_3 or 2 equiv of NaN_3 . Furthermore, the N_3^- band at 2037 cm^{-1} was the same in the presence and absence of more than 1 equiv of NaN_3 . Lehn et al.²² reported that the cryptaplex of $13\text{-N}_3^-\text{Na}^+$ in the presence of excess NaN_3 gave bands in CH_3NO_2 at 2085 cm^{-1} for the complexed azide and at 2052 cm^{-1} for the uncomplexed azide. These data clearly indicate that **1** does not capsularly complex azide ion, although in CPK models there appears to be no steric barrier to such complexation. Apparently the carbon of the $\text{C}\equiv\text{N}$ group does not carry enough positive charge to stabilize capsularly bound N_3^- .

Relative energies of the three structures **28-30** were examined in a theoretical study²³ on the structure and stability of $\text{X}^-(\text{CH}_3\text{CN})^-$, where $\text{X} = \text{F}$ and Cl , in the gas phase at absolute zero. The stabilization with $\text{X} = \text{F}$ for **28-30**, respectively, is -3.08 ,



-16.14 , and $-18.24\text{ kcal mol}^{-1}$, while for $\text{X} = \text{Cl}$, for **29** and **30**, respectively, it is -11.46 and $-10.31\text{ kcal mol}^{-1}$. The repulsion between X^- and the electronegative nitrogen of the cyano group is the destabilizing factor that makes the stabilization of **28** so much lower than the others.

The results of MM2 calculations²⁴ using a purely electrostatic model of halide ions capsularly bound by octacyanospherand (**1**) (gas phase, neglecting entropy) were found to be destabilized compared to free host and anion at infinite distance. The destabilizing ΔE values (kcal mol^{-1}) were as follows: for F^- , 15.0; for Cl^- , 13.0; for Br^- , 8.2; for I^- , 8.3. Again, the $\text{N}\cdots\text{X}^-$ repulsion was mainly responsible for the destabilization.

Spectral Properties and Conformations of the Decacyanospheraplexes and Dodecacyanospheraplexes. The ^1H NMR spectrum of decacyanospherand (**2**) in CDCl_3 , CD_2Cl_2 , $(\text{CD}_3)_2\text{-NCDO}$, and $\text{C}_6\text{D}_5\text{NO}_2$ at room and low temperatures (-60°C in CDCl_3 , -80°C in CD_2Cl_2) shows only two sharp singlets due to ArCH_3 and C_6H_2 protons, e.g., in CDCl_3 , at δ 2.62 and 7.37, respectively. This spectrum is consistent with the host possessing the $(u-d)_5$ conformation of D_{5d} symmetry. When shaken with a D_2O solution saturated with NaBr , KBr , or CsBr at 25°C , the two singlets became two multiplets, indicating that the host underwent complete conformational reorganization upon complexation. Examination of CPK models of possible conformations of complexed **2** indicates that even Cs^+ ion is not large enough to form a perching complex utilizing five upturned cyano groups in the $(u-d)_5$ conformation of the host. However, the C_{2h} structure (see drawing of **2**) with the cyano groups in the $d-m-u-d-m-u-m-d-u-m$ positions (d is down, m is middle, and u is up, starting at 12 o'clock and proceeding clockwise) provides four coplanar arylcyano groups whose sp orbitals converge on a central rectangular cavity. The diameter of this cavity in CPK models appears complementary to Cs^+ .

The ^1H NMR spectrum of dodecacyanospherand (**3**) in CDCl_3 exhibits two broad singlets at δ 2.54 (ArCH_3) and 7.44 (C_6H_2). When cooled, the aryl protons go to a broad multiplet, but the

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(22) Lehn, J.-M.; Sonveaux, E.; Willard, A. K. *J. Am. Chem. Soc.* **1978**, *100*, 4915-4916.

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Table III. Binding Free Energies ($-\Delta G^\circ$) and Association Constants (K_a) at 25 °C of Octacyanospherand (1), Decacyanospherand (2), and Dodecacyanospherand (3) Binding Alkali Metal and Ammonium Picrates in CDCl_3 Saturated with D_2O

host	$-\Delta G^\circ$, kcal mol $^{-1}$							
	Li $^+$	Na $^+$	K $^+$	Rb $^+$	Cs $^+$	NH $_4^+$	CH $_3$ NH $_3^+$	(CH $_3$) $_3$ CNH $_3^+$
1	10.6	13.5	14.1	12.6	11.8	11.8	11.2	10.0
2	11.3	12.0	13.1	13.3	13.8	12.4	11.9	11.2
3	10.7	11.4	12.6	12.7	12.9	11.9	11.5	10.7

host	K_a , M $^{-1}$							
	Li $^+$	Na $^+$	K $^+$	Rb $^+$	Cs $^+$	NH $_4^+$	CH $_3$ NH $_3^+$	(CH $_3$) $_3$ CNH $_3^+$
1	6.2×10^7	9.2×10^9	2.5×10^{10}	1.9×10^9	4.6×10^8	4.3×10^8	1.6×10^8	2.1×10^7
2	2.1×10^8	6.7×10^8	0.7×10^9	4.5×10^9	1.4×10^{10}	1.3×10^9	6.1×10^8	1.9×10^8
3	7.3×10^7	2.3×10^8	1.7×10^9	2.1×10^9	3.1×10^9	5.7×10^8	2.7×10^8	7.8×10^7

methyls still give a broad singlet. When a CDCl_3 solution of 3 was equilibrated with D_2O -saturated solutions of the alkali-metal bromides, the two broad singlets of host 3 became two doublets. These results suggest that whereas 3 in solution is an equilibrating mixture of several conformers, when complexed it becomes a single conformer containing arylcyano groups in two different kinds of environments, six in each. Examination of CPK models of this 36-membered host shows it to be very flexible. The only conformation in which more than two or three cyano groups can act cooperatively in binding the alkali-metal ions is in the (u-m-d-m) $_3$ conformation of D_{3d} symmetry. In this conformation, the *p*-CH $_3$ C $_6$ H $_2$ CN units at 1, 3, 5, 7, 9, and 11 o'clock are coplanar (see drawing of 3) with their six cyano nitrogens in a beautiful hexagonal-planar arrangement. The resulting hole is a little larger than Cs $^+$ in models. This conformation is uniquely consistent with the ^1H NMR of the complexes, the six coplanar arylcyano groups providing one type of environment and the six out-of-plane arylcyano groups providing the other.

Cation-Binding Properties of the Cyanospherands. The stoichiometry of complexation between 1–3 and various picrate salts was determined by distributing the salts between chloroform solutions, 10^{-3} M in host, and equal volumes of aqueous salt solutions at varying concentrations.²⁵ The concentrations of the picrate ion in each phase at equilibrium was determined spectrophotometrically. Plots of $[G^*]/[H]$ against $[Gi]/[H]$ were then made, in which $[G^*]$ is the concentration of complexed guest in the chloroform phase, $[H]$ is the concentration of cyanospherand in the chloroform phase, and $[Gi]$ is the initial concentration of guest in the aqueous phase.

Octacyanospherand (1) gave saturation curves at a 2 to 1 ratio of $[G^*]/[H]$ at about $[Gi]/[H] = 6.0, 5.0, 10.0,$ and 15.0 for Na $^+$, K $^+$, Cs $^+$, and NH $_4^+$, respectively (see Figure 3). Host 2 gave saturation curves at a 1 to 1 ratio of $[G^*]/[H]$ at about $[Gi]/[H] = 30, 10,$ and 5 for Na $^+$, NH $_4^+$, and Cs $^+$, respectively. Host 3 gave a saturation curve at a 1 to 1 ratio of $[G^*]/[H]$ at $[Gi]/[H] = 10$ for Cs $^+$, but saturation was not reached for Na $^+$ and NH $_4^+$, even at $[Gi]/[H] = 30$ for Na $^+$ and NH $_4^+$.

To determine the average aggregation numbers (N_{av}) of 1-KBr and 1-CsBr, equivalent amounts of host and guest were dissolved in chloroform to give 3 mM solutions. Vapor-pressure osmometry²⁶ was employed (at 46 °C) to determine N_{av} , which for each solution equaled 1.0 ± 0.1 . Thus at 10^{-3} M for both host and guest, it appears likely that essentially all complex formed does not aggregate.

The free energies of complexation ($-\Delta G^\circ$ values) were determined at 25 °C in D_2O -saturated CDCl_3 by our standard picrate extraction method on the 10^{-3} M scale for 1–3 binding Li $^+$, Na $^+$, K $^+$, Rb $^+$, Cs $^+$, NH $_4^+$, CH $_3$ NH $_3^+$, and *t*-BuNH $_3^+$ picrates (average of two determinations whose difference was <0.5 kcal mol $^{-1}$). Table III records the results. Open-chain tetramer 27 and oc-

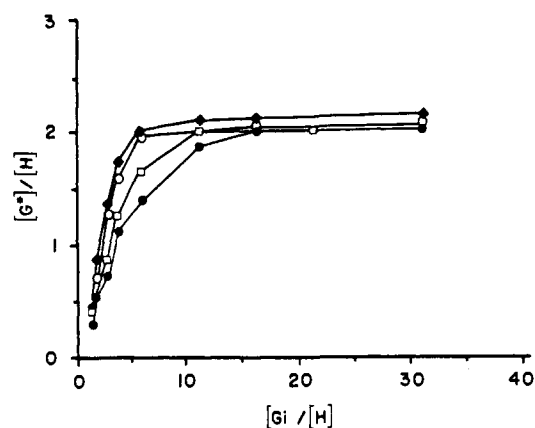


Figure 3. Complexation of octacyanospherand (1) with various cations as a function of picrate salt concentrations: \circ is for Na $^+$, \blacklozenge is for K $^+$, \square is for Cs $^+$, and \bullet is for NH $_4^+$, $[H]$ is host concentration in CHCl_3 , $[Gi]$ is initial guest concentration in H_2O , and $[G^*]$ is equilibrium concentration of guest in CHCl_3 .

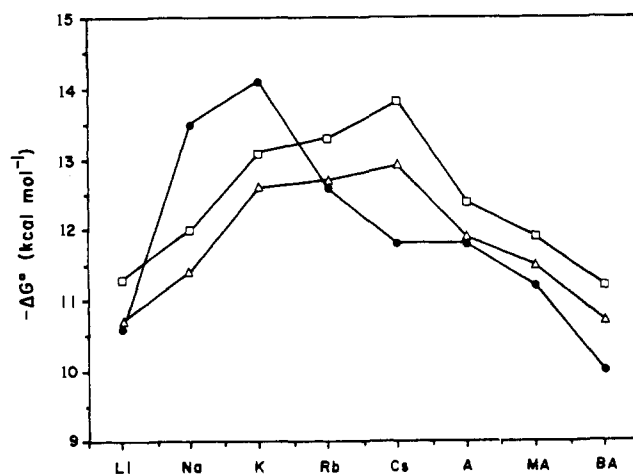


Figure 4. Graph of $-\Delta G^\circ$ (kcal mol $^{-1}$) of binding of the eight picrate salts (A is NH $_4^+$, MA is CH $_3$ NH $_3^+$, and BA is (CH $_3$) $_3$ CNH $_3^+$) at 25 °C in CDCl_3 saturated with D_2O : \bullet is octacyanospherand (1), \square is decacyanospherand (2), and \triangle is dodecacyanospherand (3).

tameric arylcyano compound 18, when submitted to the same determinations provided, $-\Delta G^\circ$ values too low to be observable (<6 kcal mol $^{-1}$).

Figure 4 is a graph that illustrates the host–guest structure-binding relationships for complexation of the eight cations and three cyanospherands. The most striking feature of these results is that all of these macrocycles bind all of the eight cations by $-\Delta G^\circ$ values that range from a high of 14.1 kcal mol $^{-1}$ for 1 binding K $^+$ to a low of 10.0 kcal mol $^{-1}$ for 1 binding (CH $_3$) $_3$ CNH $_3^+$. These values are higher than the binding of these

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(26) (a) Collins, E. A.; Bares, J.; Billmeyer, F. W. *Experiments in Polymer Science*; Wiley: New York, 1973; pp 131–135 and 374–379. (b) Shinkai, S.; Yoshida, T.; Miyazaki, K.; Manabe, O. *Bull. Chem. Soc. Jpn.* **1987**, *60*, 1819–1824.

cations by their open-chain counterparts, **18** and **27**, by >8.1 to >4.0 kcal mol $^{-1}$. Thus the power of the *preorganization of the host for binding* is again illustrated.² Of these three hosts, only the octacyanospherand is completely conformationally preorganized for binding and offers only four simultaneously binding CN: groups to a perching guest. It provides $-\Delta G^\circ_{av} = 12.0$ kcal mol $^{-1}$ for the eight guests. Host **2** appears to reorganize from a D_{3d} to a C_{2h} conformation when complexed, which provides a rectangular-planar arrangement of four CN groups for simultaneous binding with a $-\Delta G^\circ_{av} = 12.4$ kcal mol $^{-1}$ for the eight guests. The free energy cost of this reorganization must be paid for by the rectangular-planar binding to form nesting complexes. This nesting type of complex must offer greater overall stability than the perching complexes of **1**, possibly because additional water ligands for the guest in **2-G** can hydrogen bond nonligating C \equiv N: groups. Dodecacyanospherand (**3**) appears to reorganize from a mixture of rapidly equilibrating conformers to a single D_{3d} conformation upon complexation. The resulting hexagonal-planar arrangement of C \equiv N: groups offers six cyano groups that can participate in the binding to form nesting complexes with $-\Delta G^\circ_{av} = 11.8$ kcal mol $^{-1}$. Since the cavity of **3** in the D_{3d} conformation is a little larger than the ideal size even for Cs $^+$, it appears likely that Li(H $_2$ O) $_2^+$ and Na(H $_2$ O) $^+$ or Na(H $_2$ O) $_2^+$ nest in the cavity. Thus six C \equiv N: groups in **3** provide about the same average binding power as *four* in the more preorganized **1** and **2**.

The degree of structural recognition in complexation shown by the three hosts is remarkably low. Host **1** provides a maximum spread of only 4.1 kcal mol $^{-1}$, **2** of 2.6 kcal mol $^{-1}$, and **3** of 2.2 kcal mol $^{-1}$. Peak binding of **1** is observed for K $^+$, while peak binding for **2** and **3** are both observed for Cs $^+$. The largest $K_a^{M_1}/K_a^{M_2}$ values observed for each host distinguishing between two alkali-metal ions adjacent to one another in the periodic table are as follows: $K_a^{Na^+}/K_a^{Li^+} = 147$ and $K_a^{K^+}/K_a^{Rb^+} = 13.0$ for **1**; $K_a^{K^+}/K_a^{Na^+} = 7$ for **2**; and $K_a^{K^+}/K_a^{Na^+} = 7$ for **3**. All three hosts show the same tendency to bind NH $_4^+$ a little better than CH $_3$ NH $_3^+$ and CH $_3$ NH $_3^+$ somewhat better than (CH $_3$) $_3$ CNH $_3^+$. Of the three hosts, only **1** is conformationally preorganized for binding, and then only to form perching complexes in which the four ligating C \equiv N: groups leave a large portion of the guest surface exposed to water ligation, which tends to produce a leveling effect on the binding energies.

Perhaps the most surprising result is that cyanospherands **1-3** as a class bind the eight guests more strongly than do the corands as a class² and about comparably to the hemispherands.² This fact suggests that the intrinsically ligating ability of the C \equiv N: group (vs that of water) is higher than that of the ether oxygens. In this connection, it is interesting that the experimental $-\Delta H$ values (kcal mol $^{-1}$) in the gas phase for the reaction $M^+ + NCCH_3 \rightleftharpoons M^+(NCCH_3)$ varied with M^+ as follows:²⁷ Li $^+$, 43; Na $^+$, 32; K $^+$, 24.4; Rb $^+$, 20.7; Cs $^+$, 19.2.

Experimental Section

General Procedures. Tetrahydrofuran (THF) was freshly distilled from sodium benzophenone ketyl before use. Benzene, toluene, and xylene were dried over 3-Å molecular sieves activated at 330 °C for 24 h.²⁸ All reactions where anhydrous conditions were required were conducted under an argon atmosphere. Flash chromatography was carried out using silica gel 60 (E. M. Merck, particle size 0.040–0.063 mm, 230–400 mesh ASTM). Gravity columns were packed with silica gel 60 (E. M. Merck, particle size 0.063–0.200 mm, 70–230 mesh ASTM). Reverse-phase flash chromatography was performed on the support as described by Kühler and Linsten.²⁹ Thin-layer chromatography was conducted on plastic-backed, precoated silica gel plates (E. M. Merck, F254, 0.2-mm thickness) and reverse-phase plates (Whatman, KC 18F, 0.2-mm thickness). Melting points below 240 °C were measured on a Thomas-Hoover melting point apparatus, and those above 240 °C, on a Mel-Temp apparatus (uncorrected). Infrared spectra were obtained

on a Perkin-Elmer 297 grating spectrophotometer (KBr pellets) or Perkin-Elmer 580B with a Model 3600 data station (CHCl $_3$ solutions). Ultraviolet spectra were determined on a Perkin-Elmer Lambda 4 spectrophotometer. Mass spectra were recorded on an AEI Model MS-902 spectrometer at 16 or 70 eV at the temperatures indicated. FAB mass spectra were determined using xenon ionization techniques, with *m*-nitrobenzyl alcohol (NOBA) as matrix on a ZAB SE instrument (MW > 1200) or AEI Model MS-9 spectrometer (MW < 1200). 1 H NMR spectra were obtained in CDCl $_3$ solution at 200.1 MHz on a Bruker MP-200 spectrometer unless otherwise specified. 13 C NMR spectra were obtained on a Bruker AF-200 or Bruker AI 1-500 in CDCl $_3$ solution unless otherwise specified. All proton chemical shifts (δ values) are reported in parts per million using tetramethyl silane at 0.00 ppm.

2,6-Dibromo-4-methylbenzonitrile (15). This experiment is modeled after a literature procedure³⁰ for the synthesis of 2,6-dichlorobenzonitrile. To a mixture of 80 mL of water, 53.0 g (0.20 mmol) of compound **14**, and 130 mL of acetic acid was added with stirring 56.0 g (0.56 mol) of concentrated sulfuric acid. The mixture was heated to complete dissolution and then cooled to 10 °C. The aniline sulfate was diazotized at 10–13 °C with 15.4 g (0.22 mol) of NaNO $_2$ in 30 mL of water. The nitrite solution was added over the course of 10 min with vigorous stirring. Stirring was continued until the mixture became a light brown solution of the diazonium salt. Ice (100 g) was added to a solution of 38.3 g (0.24 mol) of copper(II) sulfate dissolved in 150 mL of water. To this mixture was added 65 g (1 mol) of KCN dissolved in 150 mL of water, while the temperature was kept below 20 °C by adding more ice. The voluminous precipitate that initially formed dissolved. Finally, 134.0 g (1.6 mol) of NaHCO $_3$ and 200 mL of benzene were added. To this reagent was added dropwise with vigorous stirring at 50–55 °C over the course of 20 min the above solution of the diazonium compound. After an additional 30 min stirring, 200 mL of benzene was added, and the organic phase was separated. The aqueous phase was extracted with benzene (3 \times 200 mL), and the combined organic phases were washed with 2 N NaOH solution (2 \times 200 mL) and then with brine. The organic phase was concentrated, and the crude product was crystallized from a mixture of CH $_2$ Cl $_2$ and Et $_2$ O. The product was fractionally recrystallized to purity, and the filtrates were flash chromatographed (7.5 cm \times 30 cm, 1:1 CH $_2$ Cl $_2$ /C $_6$ H $_4$) to give more material. The total product, **15**, was 31.0 g [56.4%, light yellow fluffly solid, dried at 60 °C (10 $^{-5}$ Torr) for 24 h]: mp 155–157 °C (lit.³¹ mp 156 °C); 1 H NMR δ 2.39 (s, 3 H, CH $_3$), 7.46 (d, 2 H, $J_m = 0.9$ Hz, Ar-H); 13 C NMR δ 21.65 (CH $_3$), 116.33 (–CN), 116.03, 126.58, 132.82, 146.40 (aryl carbons); IR (KBr) 2252, 1600, 868, 753 cm $^{-1}$; MS (100 °C, 70 eV) 277 (15.2, M $^+$, 81 Br + 81 Br), 275 (31.0, M $^+$, 81 Br + 79 Br), 273 (15.7, M $^+$, 79 Br + 79 Br). Anal. Calcd for C $_8$ H $_5$ NBr (MW 274.94): C, 34.95; H, 1.83; N, 5.09. Found: C, 35.00; H, 1.80; N, 5.02.

3,3'-Dibromo-5,5'-dimethyl-1,1'-biphenyl-2,2'-dicarbonitrile (16). Compound **15**, 24.0 g (0.0873 mol), was dissolved in 1.5 L of dry THF. The solution was cooled to –78 °C. A solution of 2.5 M *n*-butyllithium in hexane (34.9 mL, 0.0873 mol) was added over the course of 10 min. The reaction mixture turned black with the first drop of butyllithium. After stirring 10 min, 14.0 g (104.0 mmol, 1.2 equiv) of anhydrous copper(II) chloride [dried at 170 °C (10 $^{-5}$ Torr) for 24 h] was added all at once. The mixture was stirred for 30 min at –78 °C and then allowed to warm to 25 °C for 2 h (the reaction appeared complete at –78 °C). The whole mixture was concentrated to dryness, and the residue was dissolved in 600 mL of CH $_2$ Cl $_2$. The mixture was washed with 4 N aqueous hydrochloric acid. The organic phase was dried with brine and then over anhydrous MgSO $_4$, and the solvent was evaporated. The product, **16**, was fractionally crystallized from CH $_2$ Cl $_2$ /Et $_2$ O to give 9 g (53%) of **16**, dried at 80 °C (10 $^{-5}$ Torr) for 24 h: mp 265–267 °C; 1 H NMR δ 2.46 (s, 6 H, CH $_3$), 7.26 (s, 2 H, Ar-H), 7.61 (s, 2 H, Ar-H); IR (KBr) 2250, 1610, 870 cm $^{-1}$; MS (180 °C, 16 eV) 392 (42.9, 81 Br + 81 Br), 390 (100, 79 Br + 81 Br), 388 (42.0, 79 Br + 79 Br). Anal. Calcd for C $_{16}$ H $_{10}$ Br $_2$ N $_2$ (MW 390.08): C, 49.27; H, 2.58; N, 7.18. Found: C, 49.35; H, 2.49; N, 7.22.

3,3'''-Dibromo-5,5',5'''-tetramethyl-1,1':3',1'''-quarter-phenyl-2,2',2',2'''-tetracarbonitrile (17). Dibromide **16**, 8.0 g (0.0205 mol), was dissolved in 1.1 L of dry THF. The solution was cooled to –78 °C. A solution of 2.5 M *n*-butyllithium in hexane (8.2 mL, 0.0205 mol) was added over the course of 10 min. After stirring 10 min, 6.0 g (0.0446 mol) of anhydrous copper(II) chloride was added all at once. The mixture was stirred for 15 min at –78 °C and then allowed to warm to 25 °C for 2 h. The mixture was concentrated to dryness, and the residue was dissolved in 500 mL of CH $_2$ Cl $_2$. The mixture was washed with 4 N hydrochloric acid (3 \times 200 mL). The organic phase was dried with brine and then over anhydrous MgSO $_4$. The product was purified by gravity

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chromatography on silica gel (9 cm × 17 cm column) with CH₂Cl₂ as the mobile phase to give after crystallization 3.2 g (50%) of **17** as a white fluffy solid [dried at 80 °C (10⁻⁵ Torr) for 24 h]: mp 304–305 °C; ¹H NMR δ 2.48 (s, 6 H, CH₃), 2.56 (s, 6 H, CH₃), 7.36, 7.42, 7.50, 7.62 (s, 2 H, Ar-H); IR (KBr) 2249, 1605, 1460, 870 cm⁻¹; MS (250 °C, 16 eV), 622 (42.2, M⁺, ⁸¹Br + ⁸¹Br), 620 (100, M⁺, ⁷⁹Br + ⁸¹Br), 618 (35.9, M⁺, ⁷⁹Br + ⁷⁹Br). Anal. Calcd for C₃₂H₂₀Br₂N₄ (MW 620.35): C, 61.90; H, 3.25; N, 9.03. Found: C, 61.90; H, 3.13; N, 8.94.

3,3',3'',3'''-Dibromo-5,5',5'',5'''-5,5'',5'''-5,5'',5'''-octamethyl-1,1',1'',1'''-3,3',3'',3'''-1,1'',1'''-3,3',3'',3'''-1,1'',1'''-octaphenyl-2,2',2'',2'''-2,2'',2'''-2,2'',2'''-2,2'',2'''-octacarbonitrile (18). Dibromide **17**, 1.0 g (1.6 mmol), was dissolved in 350 mL of dry THF. The solution was cooled to -78 °C. A solution of 2.5 M *n*-butyllithium in hexane (0.7 mL, 1.75 mmol) was added over the course of 10 min. Initially the solution became pink, and then it turned brown. After 10 min of stirring, 0.4 g (3 mmol) of anhydrous copper(II) chloride was added all at once. The mixture was stirred for 15 min at -78 °C and then allowed to warm to 25 °C for 1 h. The mixture was concentrated to dryness, and then the residue was dissolved in 150 mL of CH₂Cl₂. The mixture was washed with 4 N hydrochloric acid (2 × 150 mL). The organic phase was dried with brine and then over MgSO₄. The solution was concentrated to about 5 mL, and the residue was purified by gravity column chromatography (3 cm × 26 cm, silica gel, CH₂Cl₂, and then up to 5% EtOAc in CH₂Cl₂). The product, **18**, was obtained as a fluffy white solid and dried at 80 °C (10⁻⁵ Torr) for 24 h, wt 0.160 g (18.4%): mp 220–230 °C; ¹H NMR δ 2.49 (s, 6 H, CH₃), 2.56 (s, 6 H, CH₃), 2.58 (s, 12 H, CH₃), 7.34–7.62 (m, 16 H, Ar-H); IR (KBr) 2960, 2252, 1610, 1462, 875 cm⁻¹; MS (290 °C, 70 eV) 1082 (42.4, M⁺, ⁸¹Br + ⁸¹Br), 1080 (100, M⁺, ⁷⁹Br + ⁸¹Br), 1078 (30.2, M⁺, ⁷⁹Br + ⁷⁹Br). Anal. Calcd for C₆₄H₄₀Br₂N₈ (MW 1080.88): C, 71.12; H, 3.73; N, 10.37. Found: C, 71.19; H, 3.67; N, 10.23.

Cyclization of Blaryl Dibromide, 16. This compound (5.0 g, 12.82 mmol) was dissolved in 500 mL of warm THF, and the solution was cooled to -78 °C. A solution of 1.7 M *tert*-butyllithium in pentane (33.2 mL, 56.4 mmol, 4.4 equiv) was added over the course of 15 min. Initially the reaction mixture turned dark brown (up to 1.0 equiv of *tert*-butyllithium), then light brown (1.0–2.0 equiv of *tert*-butyllithium), and finally a dark brown turbid solution (>2.0 equiv of *tert*-butyllithium). After it was stirred an additional 7 min at -78 °C, the dilithiate solution was cannulated into a refluxing solution of Fe(acac)₃ [19.90 g, 56.35 mmol, dried at 110 °C (30 Torr) for 3 days] in toluene (1.5 L) over a 30-min period with vigorous mechanical stirring (cannulation rate was controlled with argon pressure over the dilithiate solution). After an additional 2 h at reflux, the reaction mixture was cooled to 25 °C and washed with 3 N hydrochloric acid until the aqueous phase became colorless. The light brown organic solution was washed with water, dried with brine, and then dried with MgSO₄. The solution was concentrated to dryness. The residue was dissolved in 10 mL of CH₃CN, and this solution was loaded on a reverse-phase flash column²⁹ (5 cm × 14 cm). Octacyanospherand (**1**) was eluted with solution I (CH₃CN/MeOH/2 M aqueous NaBr, 2:1:1) until all of this host had eluted (~200 mL) (*R*_F = 0.06 on silica gel with 10% MeOH in CH₂Cl₂ and *R*_F = 0.64 on reverse phase with solution I). The column was then washed with solution II (CH₃CN/MeOH/1 M aqueous KCl, 5:4:1) until all of decacyanospherand (**2**) and dodecacyanospherand (**3**) eluted (~400 mL).

Purification of 4,9,14,19,24,29,34,39-Octamethylnonacyclo-[35.3.1.1^{2,6}.1^{7,11}.1^{12,16}.1^{17,21}.1^{22,26}.1^{27,31}.1^{32,36}]octatetraconta-1(41),2,4,6-(48),7,9,11(47),12,14,16(46),17,19,21(45),22,24,26(44),27,29,31(43),32,34,36(42),37,39-tetracosane-41,42,43,44,45,46,47,48-octacarbonitrile, Octacyanospherand (1). The column fractions containing octacyanospherand from the above procedure for cyclization of **16** were combined and concentrated under reduced pressure until the crude product precipitated. This material was extracted with 200 mL of CH₂Cl₂. The organic phase was separated, and the aqueous layer was extracted with 200 mL of CH₂Cl₂. The combined organic phases were dried (MgSO₄) and concentrated to 20 mL. Benzene (35 mL) was added, and the solution was allowed to stand in the hood for 2 days at ambient temperature. The resulting solid was filtered and then washed with 5 mL of benzene to give 130.0 mg of **1**. The filtrate gave an additional 23 mg of material after 1 day. The combined crops (153.0 mg) were dissolved in 300 mL of CH₂Cl₂, and the solution was filtered through a fine-glass fritted funnel. The filtrate was washed with deionized water (100 mL × 5). The solution was concentrated to 25 mL, and 5 mL of 95% ethanol was added. The solution was slowly concentrated by rotary evaporation until microcrystals formed and then cooled to 25 °C. The microcrystals were collected and washed with 0.5 mL of 95% ethanol to give 80.0 mg of **1**. The filtrate was further concentrated, and 25 mg of additional product was obtained. Half of this product (~53.0 mg) was dissolved in 5 mL of CH₂Cl₂ in a centrifuge tube (50-mL capacity) and then washed with 15 mL of deionized water five times by

vortexing (2 min) and centrifuging (2 min). The other half was similarly treated. The organic phases were combined, and 3 mL of 95% ethanol was added. The solvent was slowly evaporated at 25 °C to give 85 mg of octacyanospherand [2.8% yield, dried at 145 °C (10⁻⁵ Torr) for 24 h]. A crystal of 1·2H₂O suitable for X-ray analysis was obtained by slow evaporation of a 1:1 dichloromethane/wet methanol solution. A suitable crystal of 1·2KBr·4py was grown as follows: a methanol solution of 1.3 equiv KBr was added to a CHCl₃ solution of **1**, and then the mixed solution was concentrated. The residue was dissolved in pyridine, and the solvent was slowly evaporated to give fine white crystals: mp > 360 °C; ¹H NMR δ 2.50 (s, 24 H, CH₃), 7.31 (s, 16 H, ArH); ¹³C NMR δ 21.63 (CH₃), 114.32 (CN), 112.15, 130.53, 142.86, 143.24 (aryl C's); IR (CHCl₃) 2247, 1597 cm⁻¹; FABMS (xenon ionization) 921 (100, M + H⁺). Anal. Calcd for C₆₄H₄₀N₈·2H₂O (MW 957.1): C, 80.32; H, 4.63; N, 11.71. Found: C, 80.16; H, 4.36; N, 11.64.

Purification of 4,9,14,19,24,29,34,39,44,49-Decamethylundecacyclo-[45.3.1.1^{2,6}.1^{7,11}.1^{12,16}.1^{17,21}.1^{22,26}.1^{27,31}.1^{32,36}.1^{37,41}.1^{42,46}]hexaconta-1(51),2,4,6(60),7,9,11(59),12,14,16(58),17,19,21(57),22,24,26(56),27,29,31(55),32,34,36(54),37,39,41(53),42,44,46(52),47,49-triacontane-51,52,53,54,55,56,57,58,59,60-decacarbonitrile, Decacyanospherand (2). The eluants of the chromatographic fractions containing decacyanospherand and dodecacyanospherand from the cyclization of **16** were collected and concentrated until the solid precipitated. This material was extracted with 200 mL of CH₂Cl₂. The organic phase was separated, and the aqueous layer was extracted with an additional 200 mL of CH₂Cl₂. The combined organic phases were concentrated to about 50 mL and washed with 100 mL of deionized water four times. The organic phase was filtered through a phase-separating filter paper, and THF (30 mL) was added to the filtrate. The solution was allowed to stand for 2 days at 25 °C. The resulting white needles were collected to give 68 mg of **2** [mother liquor contained dodecacyanospherand (**3**)]. This material was recrystallized from a mixture of CHCl₃ and THF to give 46 mg [1.5% yield, dried at 110 °C (10⁻⁵ Torr) for 24 h] of **2**: mp > 380 °C; ¹H NMR δ 2.62 (s, 30 H, CH₃), 7.37 (s, 20 H, ArH); IR (KBr) 2245, 1600 cm⁻¹; FABMS (xenon ionization) 1151 (100, M + H⁺). Anal. Calcd for C₈₀H₅₀N₁₀·0.5CHCl₃ (MW 1211.03): C, 79.84; H, 4.20; N, 11.57. Found: C, 80.05; H, 4.02; N, 11.47.

Purification of 4,9,14,19,24,29,34,39,44,49,54,59-Dodecamethylundecacyclo[55.3.1.1^{2,6}.1^{7,11}.1^{12,16}.1^{17,21}.1^{22,26}.1^{27,31}.1^{32,36}.1^{37,41}.1^{42,46}.1^{47,51}.1^{52,56}]dodecaconta-1(61),2,4,6(72),7,9,11(71),12,14,16(70),17,19,21(69),22,24,26(68),27,29,31(67),32,34,36(66),37,39,41(65),42,44,46(64),47,49,51(63),52,54,56(62),57,59-hexatriacontane-61,62,63,64,65,66,67,68,69,70,71,72-dodecacarbonitrile, Dodecacyanospherand (3). The combined mother liquors from the purification of **2** were concentrated, and the residue was purified by flash column chromatography (silica gel, 3 cm × 5 cm, mobile phases in succession): CH₂Cl₂, 20% CH₃CN/80% CH₂Cl₂ (v/v); 3% MeOH/97% CH₂Cl₂ (v/v); and 5% MeOH/95% CH₂Cl₂ (v/v). The fractions containing product (TLC criteria) were combined and concentrated, and the residue was further purified by reverse-phase column chromatography (2 cm × 13 cm, CH₃CN as mobile phase). The product was recrystallized from a mixture of CH₂Cl₂ and THF to give 15 mg of pure **3** [0.5%, dried at 110 °C (10⁻⁵ Torr) for 24 h]: mp > 360 °C; *R*_F 0.5 on reverse phase with 9:1 MeOH/aqueous 2 M KBr (v/v); ¹H NMR δ 2.54 (b s, 36 H, CH₃), 7.44 (b s, 24 H, ArH); IR (KBr) 2243, 1599. FABMS (xenon ionization) 1381 (100, M + H⁺). Anal. Calcd for C₉₆H₆₀N₁₂·0.75CH₂Cl₂ (MW 1445.33): C, 80.40; H, 4.29; N, 11.63. Found: C, 80.56; H, 4.08; N, 11.47.

Cyclization of 17 to 1 and 3. The procedure used was that employed for the conversion of **16** to the 1–3 mixture with the following exceptions. Quateraryl dibromide **17** (4.15 g, 6.7 mmol) was dissolved in 600 mL of hot THF (very slow dissolution). The amount of Fe(acac)₃ employed was 10.5 g (29.7 mmol). Dilithiation of **27** was accomplished with 17.4 mL (29.6 mmol, 4.4 eq.) of 1.4 M *t*-BuLi in pentane. Initially the lithiation reaction mixture turned pink and then black. Pure octacyanospherand (**1**) (160 mg, 5%) and dodecacyanospherand (48 mg, 1%) were isolated by the above procedures.

Conformational Studies of Decacyanospherand (2) and Dodecacyanospherand (3) Employing ¹H NMR Spectra. In each of three 12-mL centrifuge tubes was transferred 0.5 mL of the host solution (1 mM in CDCl₃). Aliquots (0.5 mL) of previously prepared saturated aqueous salts (NaBr, KBr, and CsBr) were added to each tube. The two layers in each tube were mixed thoroughly using a Vortex Genie mixer for 1 min. The tubes were then placed in an International Clinical centrifuge for 2 min at high speed. The organic phases were delivered to 5-mm NMR tubes, and ¹H NMR spectra were recorded. For **2**, the two singlets at δ 2.62 and 7.37 upon complexation gave multiplets at δ 2.40–2.59 and 7.20–7.45, respectively. For **3**, the broad singlets at δ 2.54 and 7.44 each became sharp doublets of equal intensity at δ 2.52 and 2.56 and δ 7.37 and 7.39, respectively. Similar experiments conducted with octacyano-

spherand (1) produced no change in the multiplicity or chemical shift of the host's protons.

Dissolution of Tetramethylammonium Bromide by a Chloroform Solution of Octacyanospherand 1. In each of two NMR tubes were transferred 0.6 mL of octacyanospherand (1) solution (1 mM) in CDCl_3 and 0.6 mL of CDCl_3 (blank) separately. To both of these were added about 3 mg (0.02 mmol) of $(\text{CH}_3)_4\text{NBr}$. The NMR tubes were shaken for 2 min, and the ^1H NMR spectra were recorded. Aliquots (0.2 mL) of D_2O were added to each NMR tube. The two layers were mixed by shaking the NMR tubes for 1 min. The organic phases were separated, and the ^1H NMR spectra were recorded. In the blank test a weak peak corresponding to the methyl groups of ammonium ion was detected at 3.16 ppm only when the CDCl_3 was saturated with D_2O . The ^1H NMR spectrum of the dry host solution gave signals for $(\text{CH}_3)_4\text{NBr}$ at δ 2.79 (12 H) and octacyanospherand at δ 2.50 (24 H, CH_2) and 7.31 (16 H, ArH), corresponding to one-to-one complexes. Moreover, the chemical shifts of complexed and noncomplexed octacyanospherand were always identical. When shaken with D_2O , the guest always went into the D_2O layer. Similar experiments were attempted with a wide variety of salts (KBr, CsBr, NaN_3 , NaClO_4 , and Bu_4NBH_4), but the ^1H NMR peaks of the octacyanospherand did not change upon complexation.

Attempts to Complex Octacyanospherand (1) with Tetrabutylammonium Borohydride. Octacyanospherand (1) (10.0 mg) was dissolved in CDCl_3 in a 2-mL volumetric flask to give a 5.4 mM solution. Tetrabutylammonium borohydride (7.0 mg) was dissolved in CDCl_3 in a 5-mL volumetric flask to give a 5.4 mM solution. A 0.5-mL aliquot of the 5.4 mM borohydride solution was delivered to a 5-mL volumetric flask, which was filled to the mark with CDCl_3 to give a 0.54 mM solution. In each of two 5-mm NMR tubes was transferred 0.5 mL of the borohydride solutions. Aliquots (0.5 mL) of octacyanospherand solution were added to each tube. The tubes were shaken for 30 min, and then the ^1H NMR spectra were recorded from +25 to -60 °C. The ^1H NMR spectra of each of the solutions gave the same borohydride peak. ^1H NMR δ -0.01 (q, 4 H, J = 81 Hz).

Changes in the ^{13}C NMR Spectrum of Octacyanospherand 1 upon Complexation. The above host (50.0 mg) was dissolved in $(\text{CD}_3)_2\text{SO}$ in a 5-mL volumetric flask, and 20.0 mg of octacyanospherand was dissolved in CDCl_3 in a 2-mL volumetric flask to give 1.1×10^{-2} M solutions. In each of five 5-mm NMR tubes was transferred 1.0 mL (0.01 mmol of 1 per tube) of the $(\text{CD}_3)_2\text{SO}$ solution of octacyanospherand, and in each of two additional 5-mm NMR tubes was transferred 1.0 mL of CDCl_3 solution (0.01 mmol of 1 per tube) of octacyanospherand. The ^{13}C NMR spectrum of each solution was recorded. To each of the five NMR tubes containing the $(\text{CD}_3)_2\text{SO}$ solutions of octacyanospherand was added successively solid NaBr (45.2 mg, 0.4 mmol), CsBr (42.6 mg, 0.2 mmol), Me_4NPF_6 (21.9 mg, 0.1 mmol), and Bu_4NI (36.9 and 110.8 mg, 0.1 and 0.3 mmol, respectively). In each of two NMR tubes containing the CDCl_3 solution of octacyanospherand was added successively Me_4NBr (1.0 mg, 0.0063 mmol) and Et_4NBr (6.3 mg, 0.03 mmol). The salts were completely dissolved by vigorous mixing and mild heating in some cases. The ^{13}C NMR spectrum was measured with a Bruker AF-200 instrument. The spectra of salt-containing solutions were compared with those of free octacyanospherand for each experiment. The results are summarized in Table II. The ^{13}C NMR spectra for uncomplexed host (1) gave the following signals. ^{13}C in CDCl_3 δ 21.63 (C_6), 112.15 (C_2), 114.32 (C_1), 130.53 (C_4), 142.86 (C_5), 143.24 (C_3); in $(\text{CD}_3)_2\text{SO}$ δ 21.05 (C_6), 111.13 (C_2), 113.94 (C_1), 130.28 (C_4), 142.15 (C_5), 142.98 (C_3).

Experiments Conducted To Determine the Effects of Complexation on the IR Spectra of Octacyanospherand (1) and Sodium Azide. In each of two flasks were placed successively 0.33 mg (5.0×10^{-3} mmol) of NaN_3 and 0.77 mg (5.0×10^{-3} mmol) of $(\text{CH}_3)_4\text{NBr}$. Each salt was dissolved with a minimum amount of CH_3OH . Octacyanospherand (4.6 mg, 5.0×10^{-3} mmol) was added to each salt solution, and the mixtures were dissolved in CHCl_3 . The resulting solutions were concentrated to dryness under reduced pressure. The residues were dried at 0.1 Torr for 3 h and then redissolved in CHCl_3 . The IR spectrum of each solution was taken on a Perkin-Elmer 580B IR spectrometer. To the solution containing NaN_3 and octacyanospherand was added NaN_3 solution (1 mg) in CH_3OH , and then the solvent was evaporated. The residue was dissolved in CHCl_3 , and the IR spectrum of this solution was recorded. The results are reported in the text.

Measurements of Average Molecular Weights of Octacyanospherand (1). In each of two 5-mL ampules were placed successively 1.07 mg (9 mmol) of KBr and 1.92 mg (9 mmol) of CsBr, and each salt was dissolved with a minimum amount of CH_3OH . An aliquot of 3 mL of CHCl_3 solution of octacyanospherand (3 mM) was added to each am-

pule. The solvent was evaporated at 65 °C in an oil bath. The residues were further dried at 65 °C (0.1 Torr) for 5 h. An aliquot of 3 mL of chloroform was added to each ampule, and then the ampules were sealed. The residues were completely dissolved by sonication. The average molecular weights were measured at Galbraith Laboratories. The results are summarized in the text.

Determination of the Stoichiometry of Complexation of Hosts 1-3. This procedure is a modification of the picrate extraction experiments reported previously.³² The values of the extinction coefficient in acetonitrile at 380 nm for picrate salts determined earlier were used here. All operations were conducted at 24-26 °C. Absorbances were determined at 380 nm with a Perkin-Elmer Lambda 4B UV/vis spectrophotometer. Spectral-grade CH_3CN and deionized water were used throughout.

Aqueous solutions of 0.0005, 0.001, 0.002, 0.003, 0.005, and 0.010 M were prepared of the picrates of Na^+ , K^+ , and NH_4^+ by diluting a 0.015 M aqueous solution of the corresponding picrate with deionized water. For Cs^+ , aqueous solutions of 0.0005, 0.001, 0.002, 0.003, and 0.005 M were prepared by diluting 0.010 M aqueous solution of cesium picrate. In each of eight (seven for Cs^+) 12-mL centrifuge tubes was transferred 0.50 mL of the picrate solutions of the same cation with a Lab Industries micropipet (the more concentrated guest solution than 0.15 M was prepared by using 1 mL of the previous solution). Aliquots (0.50 mL) of a previously prepared CDCl_3 solution that was 0.001 M in host were added with micropipet to each tube. The tubes were covered immediately with rubber septums. The two layers in each tube were mixed thoroughly using a Vortex Genie mixer for 1 min. The tubes were then placed in an International Clinical centrifuge for 3 min at high speed. Aliquots of 100 μL of the organic phase were very carefully removed from each phase with a Hamilton Gastight syringe and transferred to 5-mL volumetric flasks, which were filled to the mark with acetonitrile. The absorbance of each sample was then measured and the complexed picrate concentration $[\text{G}^*]$ in the organic phase was calculated using Beer's law.

Crystal Structure Determinations. Compound 1-2KBr-4py crystallizes from pyridine as pale yellow multifaceted crystals in the tetragonal systems $P4/nmc$. Unit cell dimensions are as follows: a = 18.630 (3), c 10.443 (2) Å; V = 3623 Å³, Z = 2 (16 one-eighth molecules). The crystal was examined on a modified Picker FACS-1 diffractometer, Mo $K\alpha$ radiation, at 128 K. The structure was determined by direct methods. Refinement of 54 parameters (1076 reflections with $F > 3\sigma(F)$) has an agreement value, R , currently at 0.17. Each host possesses 422 symmetry. A 4-fold axis and two 2-fold axes intersect at the center of the host. The potassium cation is located on a 4-fold axis, and the disordered bromide anion is located on a 2-fold axis. Pyridine is located about the 4-fold axis in position to complete the coordination sphere of the potassium. This compound is arranged in stacks, with channels filled by the cation running through the center of the host and with parallel channels occupied by anion running between hosts.

Compound 1-2H₂O crystallizes from a 1:1 CH_2Cl_2 /wet CH_3OH solution as small clear pale yellow platelets in the tetragonal system $P4n2$. Unit cell dimensions are as follows: a = 11.854 (1), c = 19.539 (2) Å; V = 2759 Å³, Z = 2 (8 quarter molecules). The crystal was examined on a diffractometer constructed by Professor C. E. Strouse of this department using Mo $K\alpha$ radiation, at 25 °C. The structure was determined by direct methods. Refinement of 94 parameters (789 reflections with $I > 3\sigma(I)$) led to an agreement value, R , currently at 0.10. Each molecule has 222 symmetry; i.e., three intersecting 2-fold axes pass through the center of the host. Water is located on one of these 2-fold axes.

Compound 1-2H₂O, in contrast to the cyanospherplex, does not organize in stacks but has a herringbone packing such that axes through oxygen atoms nearest each host are perpendicular to each other.

Compound 26 crystallizes from CH_2Cl_2 /dimethylformamide as pale bronze parallelepipeds in the monoclinic system Aa . Unit cell dimensions are as follows: a = 11.428 (1), b = 8.1217 (9), c = 13.579 (2) Å; β = 98.331 (4)°; V = 1247 Å³, Z = 4. The crystal was examined on a modified Picker FACS-1 diffractometer, Mo $K\alpha$ radiation, at 25 °C. The structure was determined by direct methods. Refinement of 71 parameters (680 reflections with $I > 3\sigma(I)$) led to an agreement value, R , currently at 0.10.

Coordinates for these compounds will be deposited with the Cambridge Data File.

(32) (a) Koenig, K. E.; Lein, G. M.; Stücker, P.; Kaneda, T.; Cram, D. J. *J. Am. Chem. Soc.* 1979, 101, 3553-3566. (b) Koenig, K. E.; Helgeson, R. C.; Cram, D. J. *Ibid.* 1976, 98, 4018-4020.