Pergamon

SCIENCE DIRECT®

Tetrahedron 59 (2003) 231–239

TETRAHEDRON

Metal-containing ditopic receptors for molecular recognition of diammonium cations

Olga P. Kryatova, Alexander G. Kolchinski and Elena V. Rybak-Akimova*

Department of Chemistry, Tufts University, 62 Talbot Avenue, Medford, MA 02155, USA

Received 10 July 2002; accepted 8 November 2002

Abstract—Two new ditopic receptors for α,ω-alkanediyldiammonium cations based on a tetraazamacrocyclic (cyclidene) nickel(II) complex bearing two crown-ether residues were synthesized. The studies of the host–guest interaction between the receptors and a series of α,ω-diammonium salts by NMR titration in acetonitrile-d_3 showed that 1:1 complexes are formed with $K_{assoc} \sim 10^3 - 10^5$ M^{-1}. Receptor **1** with benzo-15-crown-5 arms showed substantial selectivity in binding of trimethylene- and tetramethylenediammonium dications, and 1–2 orders of magnitude weaker binding of shorter (C_2) or longer (C_5 and C_6) diammonium cations. Receptor **2** with benzo-18-crown-6 arms showed higher affinity to all studied diammonium cations, but the recognition of the length of α,ω-diammonium cations was less pronounced.

1. Introduction

Multipoint recognition of organic molecules is an efficient way of designing size- and shape-selective receptors with high affinity for substrates.[1–4] Unraveling the factors that govern selectivity in host–guest binding is also important for better understanding of molecular recognition in biochemical processes. Incorporation of the metal ions into multicenter receptors offers several potential advantages,[5–7] such as: (1) metal ion may act as an additional binding site; (2) metal ions are reactive sites, allowing for selective substrate transformations; (3) reactivity and binding properties of the metal center can be altered, e.g. by changing the oxidation states; or (4) the shape of the receptor molecule can be regulated via reversible reactions at the metal center.

We report the preparation of two ditopic hosts for diammonium salts based on a metal-containing macrocyclic platform (cyclidene)[8–10] bearing two crown-ether receptor sites. The distinctive features of the cyclidene scaffold include the relative flexibility of the cleft,[11,12] which in principle allows for the regulation of the substrate affinity and selectivity via conformational changes in the platform, and the positioning of the guest right above the metal center, thus suggesting potential involvement of the metal in the catalytic regioselective transformations of the substrates. Examples of regioselective reagents and catalysts based on functionalized rigid metalloporphyrins were provided by Breslow[13–19] and Woggon.[20–22] Unlike porphyrins, the 15-membered cyclidene platform can adopt both 'open' (planar) and 'closed' (saddle shaped) conformations.[9] This dual-shape feature is needed in order to eventually obtain switchable receptors. Earlier we prepared a receptor for dicarboxylic acids based on a nickel(II) cyclidene platform with two cyclic tetramine (cyclen) binding sites, which displayed notable length and shape-selectivity.[23] In the case of carboxylate recognition, the electrostatic interaction between the dipositive metal ion in the platform and negatively charged guest was favorable for the inclusion complex formation.

We set out to determine whether ditopic selective guest binding is possible in the presence of unfavorable electrostatic interaction between the metal cation in the cyclidene platform and cationic substrates. Protonated organic amines were chosen as guests, because amine functionality is commonly present in biomolecules, such as amino acids, proteins and neurotransmitters. Crown ethers, which are known to form reasonably strong complexes with primary ammonium salts,[24] were selected as receptor groups. The molecules containing two crown ether fragments attached to a rigid scaffold or assembled about a metal center were shown to bind diammonium salts and, in some cases, displayed substantial length selectivity.[25–38] In the present study, either high affinity (B18C6) or low affinity (B15C5) binding groups were attached to the cyclidene platform, and the affinity and selectivity of the resulting ditopic receptors toward diammonium guests were compared.

2. Results and discussion

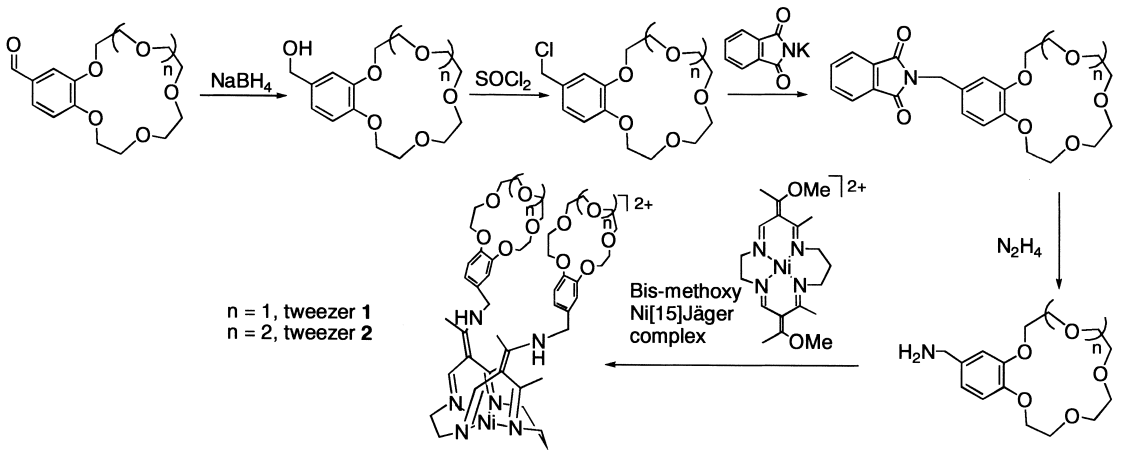
2.1. Synthesis

The synthesis of molecular tweezers **1** and **2** is outlined

Keywords: diammonium cations; receptors; binding properties.

* Corresponding author. Tel.: +1-617-627-3413; fax: +1-617-627-3443; e-mail: elena.rybak-akimova@tufts.edu

0040–4020/03/$ - see front matter
PII: S0040-4020(02)01482-5



Scheme 1.

in Scheme 1. The preparation of receptor molecules **1** and **2** is based on a general reaction of the *O*-alkylated Jäger macrocycle ($[Ni[(MeOEthi)_2Me_2[15]tetraeneN_4]](PF_6)_2$) with primary amines developed by Busch and co-workers.[9] The aromatic amino group is far less reactive and can hardly be attached to Jäger platforms.[39,40] A limited number of sterically non-hindered aliphatic secondary amines react smoothly with Jäger macrocycles,[39,41,42] although in many cases steric hindrance prevents or retards cyclidene formation.[39,43] Additionally, strong bases (such as secondary amines) promote deacylation of Jäger and cyclidene macrocycles.[40,44] Consequently, aza-crowns or aminobenzocrowns were inappropriate precursors for cyclidene-based molecular tweezers. Aminomethyl-substituted benzocrowns, which are better suited for attaching to the edges of Jäger macrocycles, were prepared from the corresponding hydroxymethyl benzo crowns (Scheme 1). Initial attempts to synthesize the 4-aminomethylbenzocrowns via reductive amination of the corresponding formyl-benzocrowns did not succeed and were not pursued further.

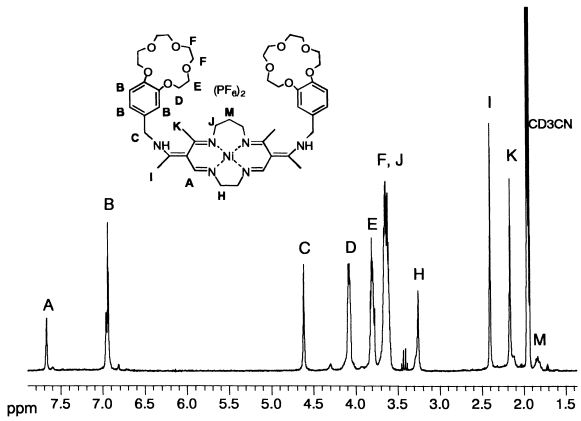


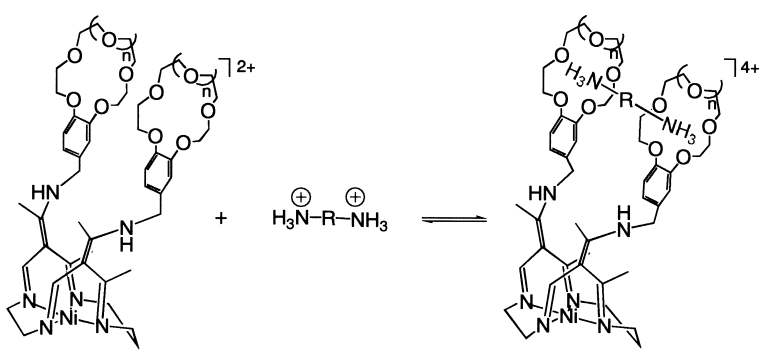
Figure 1. ^1H NMR spectrum of tweezer **1** in CD_3CN.

Attaching aminomethyl-benzocrowns to *O*-methylated Jäger platforms proceeded uneventfully and yielded target compounds **1** and **2**, which were characterized by elemental analysis, mass-, UV–Vis and NMR spectroscopy (see Section 4). The assignment of the NMR spectra was based on previously published data for similar compounds.[42,45]

The ^1H NMR spectrum of compound **1** is shown in Figure 1. The signals of the protons of the cyclidene platform are relatively broad with varying intensity, especially signal M, but the integration is in agreement with the assignment. The broad peaks of the cyclidene methylene groups can be explained by 'flexing' of the platform.[46,47]

2.2. Reactions with ammonium salts

Host–guest interaction between receptors and diammonium salts (Scheme 2) was studied by ^1H NMR titration in CH_3CN-d_3; typical spectral changes are shown in Figure 2. Addition of a diammonium salt to the acetonitrile solution of a tweezer resulted in chemical shift changes for the protons of the host and guest. For the host, both the receptor



Scheme 2.

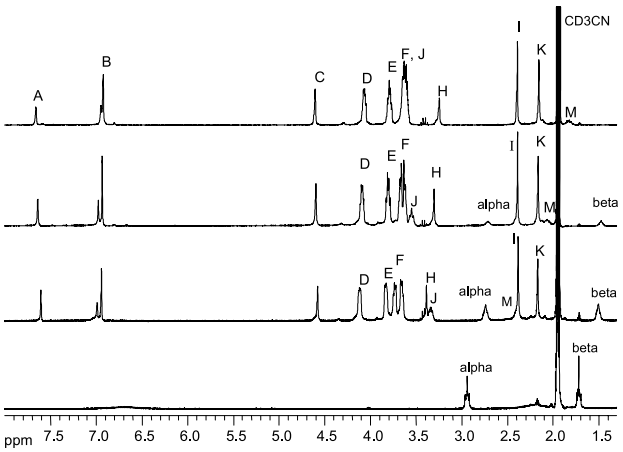
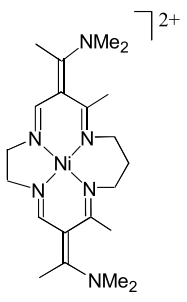


Figure 2. ^{1}H NMR spectra of acetonitrile solutions of pure tweezer **1** (10^{-2}M); tweezer **1** and tetramethylenediammonium thiocyanate in ratio 2.5:1 and 1:1; pure tetramethylenediammonium salt (from top to bottom).

crown arms and the tetraazamacrocyclic platform signals shifted, but to a different extent. The protons of the crown residues showed only a slight upfield shift (≤15 Hz), while the protons of the tetraazamacrocyclic platform shifted by 20–170 Hz. This trend cannot be interpreted in terms of a direct coordination of the guest to the cyclidene platform rather than to the appended crown ethers, because no interaction between the diammonium guests and a nickel(II) macrocycle **3** lacking crown ether residues (Scheme 3) was observed by NMR. Small changes in the NMR spectra of crown ethers upon alkylammonim cation binding are common.[28,48,49] The most pronounced changes occurred for the signals of the methylene groups (J and M) of the tertrazamacrocyclic platform, which are remote from the guest binding sites (Fig. 2). The methylene signal M at δ 1.85 ppm shifted downfield by ~0.33–0.56 ppm (100–170 Hz). Signal *J* overlapped with the signal of methylene protons of crown residue in the spectrum of free tweezers and shifted upfield by ~0.25–0.4 ppm (73–128 Hz) upon binding with a diammonium cation (Table 1).

The addition of a monoammonium salt (benzylammonium perchlorate) to the acetonitrile solution of the tweezers **1** or **2** did not cause such a drastic change in the ^{1}H NMR spectra of the tweezer: only chemical shifts by ≤10 Hz were observed (Table 1). However, the signals of the monofunctional guest were shifted, indicating that the complexation between the monoammonim cation and the crown ethers appended to the cyclidene platform occurred. This result



3

Scheme 3.

Table 1. Maximum changes in the chemical shift of the protons of CH_2-groups of the cyclidene platform for tweezers **1** and **2** (signals J and M; Fig. 2) due to the complexation with substrates. CD_3CN, T=298 K, $C_{(\text{tweezer 1})}=1.0\times10^{-2}$ M, $C_{(\text{tweezer 2})}=1.0\times10^{-3}$ M

Cation-substrate	$\Delta_{max}\delta$ (Hz)			
	J		M	
Tweezer **1**	Tweezer **2**	Tweezer**1**	Tweezer **2**	
$(CH_2)_2(NH_3)_2^{2+}$	73	84	119	>100[a]
$(CH_2)_3(NH_3)_2^{2+}$	95	121	181	115
$(CH_2)_4(NH_3)_2^{2+}$	102	128	182	>100[a]
$(CH_2)_5(NH_3)_2^{2+}$	66	122	144	>100[a]
$(CH_2)_6(NH_3)_2^{2+}$	62	100	162	180
$(C_6H_4)(CH_2)_2(NH_3)_2^{2+}$	81	120	150	>100[a]
$(C_6H_5)(CH_2)(NH_3)^{+}$	<10[a]	<10[a]	10	10

[a] It was impossible to find the exact value because of overlapping of the signals.

strongly suggests that both protonated mono- and diamines interact with the crown ether receptor sites, but their binding modes are different. Unlike monofunctional guests, the diammonium cations can be encapsulated between both receptor 'arms', causing a conformational change of the cyclidene macrocycle upon complexation with ditopic substrates. Similar conformation-dependent NMR shifts of monoalkylated cyclidene complexes have been reported.[46,47] The changes in the chemical shift of the CH_2 groups J and M upon ditopic substrate binding might also be due to the proximity of the aromatic π-systems of the benzocrown residues in the complexes.

Unfortunately, the signals of the platform could not be used to monitor the equilibrium by NMR titration because they overlapped with several other signals during the titration. It was convenient to follow the reactions by measuring the changes in the chemical shifts of the α-CH_2 groups of the diammonium cations. These signals did not overlap with other signals and were highly sensitive to complex formation (Fig. 2, Table 2). Addition of an excess of the parent monotopic host (benzo-15-crown-5 or benzo-18-crown-6) to diammonium cations caused a smaller change in the chemical shift of the aliphatic protons of cations compared to the titration with equivalent amounts of ditopic tweezers **1** or **2**, respectively (Table 2). These results agree with the ditopic binding of diammonium salts with both receptor sites of the tweezers.

The stoichiometry of the host–guest complexes was established by Job's method of continuos variations.[50] The

Table 2. Maximum changes in the chemical shift of the protons in the difunctional guest (hexamethylenediammoium cation) upon interaction with crown ether-containing hosts. CD_3CN, T=298 K, $C_{(\text{dication})}=1.0\times10^{-2}$ M

Host	$\Delta_{max}\delta$ for the protons of $(NH_3)_2(CH_2)_6^{2+}$ (Hz)		
	α	β	γ
B15C5	42	54	66
Tweezer **1**	52	68	77
Tweezer **2**	70	113	109
B18C6	55	88	91

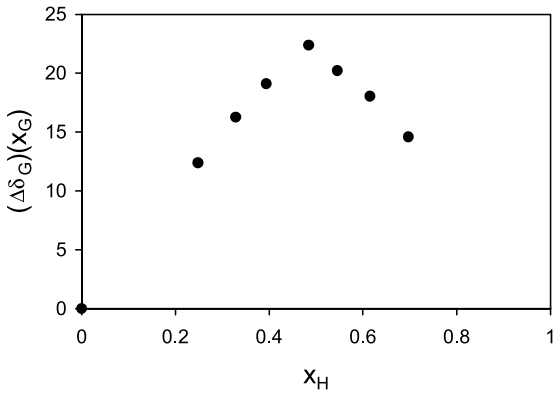


Figure 3. Job's plot for the system containing tweezer **1** and hexamethylenediammonium salt in CD_3CN. The total concentration of the host (H) and the guest (G) was kept constant at 2×10^{-2} M. The change in the proton chemical shift of the αCH_2 group of hexamethylenediammonum cation (G) was followed. The value $(\Delta\delta_G)(x_G)$, where x_G denotes molar fraction of the guest, was plotted vs molar fraction of the host (x_H).

Job's plot for the system tweezer **1**–hexamethylendiammonium thiocyanate is shown, as an example, in Figure 3, where the complexation-induced shift of guest ^{1}H NMR resonance was followed as a function of the host mole fraction, keeping their total concentration constant.[50] In all tweezer–diammonium cation systems, 1:1 complexes were found by Job's method in agreement with the bidentate inclusion of the guest depicted in Scheme 2. Control experiments showed a 2:1 complexation between simple parent crowns (B15C5 or B18C6) and diammonium cations, a 1:2 complexation between ditopic tweezer (**1** or **2**) and monoammonium cations, and a 1:1 complexation between monotopic crowns (B15C5 or B18C6) and monoammonium cations. These observations, as well as similar behavior of 15C5 and 18C6 derivatives in our experiments, suggest that under our experimental conditions, each RNH_3^+ group interacts with one crown ether ring. An alternative possibility exists for the B15C5 derivatives, where two types of complexes with monoamonium salts in either 1:1 or 2:1 ratios could be formed, and their binding constants were comparable.[51] In the 2:1 complexes, one ammonium group is sandwiched between two crown ether rings. In principle, one terminal ammonium group of the difunctional guest could be sandwiched between two receptor sites of the

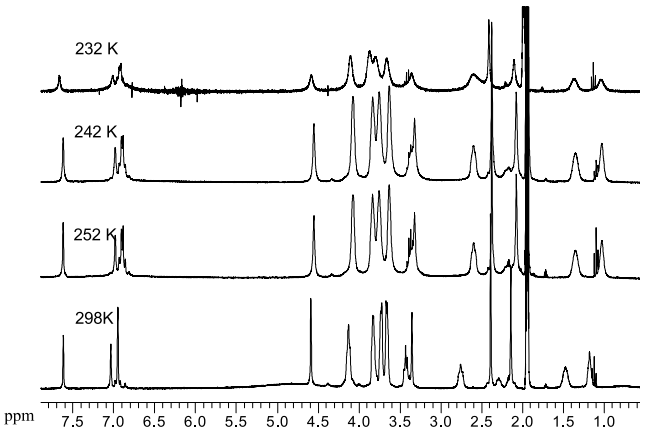


Figure 4. ^{1}H NMR spectra of the acetonitrile solution containing tweezer **1** (10^{-2} M) and tetramethylenediammonium thiocyanate in a ratio 1:1 at different temperatures.

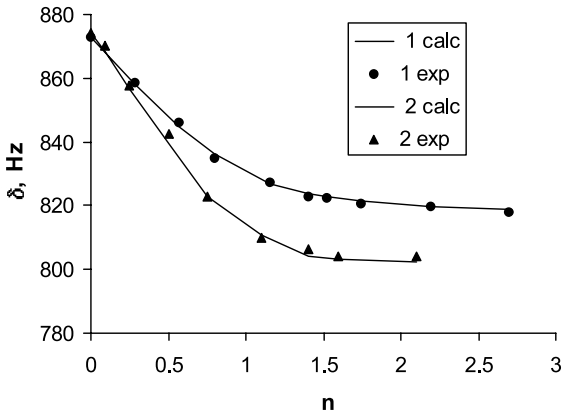


Figure 5. ^{1}H NMR-titration curves of hexamethylenediammonium thiocyanate with tweezer **1** (curve 1) ($C_{dication}=10^{-2}$ M) and tweezer **2** ($C_{dication}=10^{-3}$ M) (curve 2): proton chemical shift of αCH_2 group in diammonium cation vs amount of equivalents of the tweezer added.

B15C5-containing host **1**, leaving the second ammonium group uncoordinated. In a slow exchange rate, encapsulated binding mode (Scheme 2) could be distinguishable by NMR from the 'sandwiched' binding mode of the diamine.

The variable temperature experiment was performed for the solution containing tweezer **1** and hexamethylenediammonium thiocyanate in a 1:1 ratio (Fig. 4). With decreasing temperature, the signals of the CH_2 groups of the cation became slightly broader and were shifted upfield, indicating that the yield of the host–guest complex increases at lower temperatures as is expected for an association process. Cooling the sample also caused the signals J and M of the tweezer platform to broaden slightly and to move upfield, again showing an equilibrium shift toward formation of the host–guest complex. Although the low temperature NMR experiment was inconclusive, the stoichiometry of the complexes (1:1 for **1**+diammonium guest vs 1:2 for **1**+monoammonium guest) and the amine length selectivity displayed by host **1** (see below) agree with the bindentate inclusion of the diamines (Scheme 2).

Association constants for 1:1 host–guest complexes were determined from the binding curves (Fig. 5) by nonlinear regression methods that gave excellent fits to a 1:1 model for the association between a host and guest. The results of the ^{1}H NMR titrations of the diammonium salts (thiocyanate or perchlorate) with the ditopic molecular receptors are summarized in Table 3.

A dipositive charge localized in the platform does not negatively affect the binding as can be seen from comparing the binding affinities of the ditopic receptors **1** and **2** with the corresponding data for the binding of monoammonium salts by simple benzo crowns. A moderate chelate effect was registered for the B18C6 derivative **2**, while a substantial increase in alkyl diammonium binding affinities was registered in several cases for the B15C5 derivative **1** (Table 3). As expected, B18C6-containing host **2** displays higher guest binding affinities than its B15C5-containing counterpart **1**. This behavior parallels guest binding affinities of monomeric crown ethers.[24,52,53]

The recognition of the length of α,ω-diamines was

Table 3. Association constants (K_{assoc}, M^{-1}) for 1:1 host–guest complexes of tweezers **1** and **2** and benzocrowns with diammonium and monoammonium cations at 298 K

Host	Guest	K_{assoc}	log K_{assoc}	Method	Solvent
B15C5	NH_4^+		2.16	Calorim[51]	CH_3CN
			2.30	NMR[48]	CH_3CN
			3.03	Potent[70]	MeOH
	$NH_3(CH)_2C_6H_5^+$	5.5×10^2	2.74	NMR, ^1H	CH_3CN
Tweezer **1**	$(NH_3)_2(CH_2)_2C_6H_4^{2+}$	3×10^3	3.48	NMR, ^1H	CH_3CN
	$(NH_3)_2(CH_2)_2^{2+}$	4×10^3	3.60	NMR, ^1H	CH_3CN
	$(NH_3)_2(CH_2)_3^{2+}$	5×10^4	4.70	NMR, ^1H	CH_3CN
	$(NH_3)_2(CH_2)_4^{2+}$	1×10^5	5.00	NMR, ^1H	CH_3CN
	$(NH_3)_2(CH_2)_5^{2+}$	4×10^3	3.60	NMR, ^1H	CH_3CN
	$(NH_3)_2(CH_2)_6^{2+}$	1.25×10^3	3.10	NMR, ^1H	CH_3CN
B18C6	NH_4^+		4.14	Potent[70]	MeOH
	NH_4^+		4.27	Calorim[71]	MeOH
	NH_4^+		4.07	Calorim[24]	CH_3CN
	t-$BuNH_3^+$	3.5×10^3	3.54	NMR[24]	CH_3CN
	$NH_3(CH)_2C_6H_5^+$	5×10^4	4.70	NMR, ^1H	CH_3CN
Tweezer **2**	$(CH_3)_2(NH_2)_2(CH_2)_2^{2+}$	1.2×10^2	2.08	NMR, ^1H	CH_3CN
	$(NH_3)_2(CH_2)_2^{2+}$	3×10^4	4.48	NMR, ^1H	CH_3CN
	$(NH_3)_2(CH_2)_3^{2+}$	7×10^4	4.85	NMR, ^1H	CH_3CN
	$(NH_3)_2(CH_2)_4^{2+}$	9×10^4	4.95	NMR, ^1H	CH_3CN
		6×10^2	2.78	NMR, ^1H	MeOH
	$(NH_3)_2(CH_2)_5^{2+}$	3×10^4	4.48	NMR, ^1H	CH_3CN
	$(NH_3)_2(CH_2)_6^{2+}$	2×10^4	4.30	NMR, ^1H	CH_3CN
		3×10^2	2.48	NMR, ^1H	MeOH
	$(NH_3)_2(CH_2)_2C_6H_4^{2+}$	5×10^4	4.70	NMR, ^1H	CH_3CN

investigated on a series of aliphatic difunctional guests with two primary ammonium groups separated by 2–6 carbons. Tweezer **1** bearing B15C5 arms showed substantial selectivity, with the strongest complexation of trimethylene- and tetramethylenediammonium cations, and 1–2 orders of magnitude weaker binding of a shorter (C_2) or longer (C_5 and C_6) diammonium salts (Table 3). The chemical shift changes of the CH_2-groups in the cyclidene platform of the tweezer **1** due to the addition of different diammonium salts also depended on the lengh of the diammonium cation, as shown in Table 1. The largest shifts were observed with tetramethylenediammonium and trimethylenediammonium cations indicating that these cations provide the best fit. The optimal length of the diamine guests agrees well with the cavity width of saddle-shaped cyclidenes (ca. 7 Å).[9] The results of molecular modeling studies on covalently bridged cyclidene systems[11,12,54] also demonstrated that the six-atom (C_6) linker spans the cavity with the least steric strain.

The guest binding affinity of the B18C6-containing tweezer **2** reveals the same trend in optimal length of the diammonium substrates as were seen for the tweezer **1**, although the length selectivity is significantly less pronounced (Table 3). Values of the chemical shifts of the methylene protons from the cyclidene platforms were virtually independent of the nature of the diammonium cation in this case (Table 1). It appears that the higher guest binding affinity of tweezer **2** masks its potential selectivity in encapsulating diammonium substrates of different length. Indeed, the equilibrium constants for supramolecular host–guest complexes with tweezer **2** show strong binding for all primary diammonium cations (Table 3). The NMR titration of the diammonium salts with the strongest and weakest binding (C_4 and C_6 chains, respectively) was also done in methanol. As expected, in the protic solvent binding constants were lower than in acetonitrile, but the difference in the values of log K_{assoc} remained small (Table 3).

It is likely that the relatively small energy penalty upon reorganization of the host in order to bind a 'non-optimal' guest is sensed by the low-affinity receptor **1**, but does not lead to discrimination against non-optimal guests by the high-affinity receptor **2**. It is also possible that the larger rings of 18C6 receptor sites allow for an easier accommodation of diammonium substrates of different length between the receptor arms. In ammonium complexes with B18C6, both 'perched' and 'nested' geometries are possible, where three symmetric hydrogen bonds are formed between the ammonium group and three oxygen atoms of the crown in its preferred D_{3d} conformation. In the former case, the ammonium atom lies 0.8–0.9 Å above the mean plane of the oxygen atoms. In the latter case, which is easily accessible when its stability is enhanced by other interactions (such as additional hydrogen bonds in $H_3NNH_3^{2+}$ complex), it moves almost to the center of the ring and is bound to the lower triangle of 18C6 oxygens.[55–57] In contrast, only the perching complexes are stable for the B15C5 derivatives, with the ammonium group located ca. 2.0 Å above the mean plane of the oxygen atoms.[57]

Strong binding affinity of the B18C6 derivative **2** is also exemplified in the ability of this host to complex secondary diamines (Table 3). There was no evidence for piperidine binding to the complex **1** under our experimental conditions.

3. Conclusion

In the present study, two compounds based on a nickel(II) cyclidene platform bearing two crown-ether receptors (B18C6 or B15C5) were synthesized. Studies of host–guest

interaction between the tweezers and α,ω-diammonium cations by ^{1}H NMR titration in CD_3CN showed that 1:1 complexes are formed with $K_{assoc} \sim 10^3 - 10^5\ M^{-1}$. B15C5-derivative (**1**) showed substantial selectivity in binding of trimethylene- and tetramethylenediammonium cations. Higher affinity of the B18C6 receptor arms of host **2** to the diammonium substrates resulted in stronger, but less selective binding properties.

4. Experimental

4.1. General

Chemicals (reagent grade) and solvents were purchased from Aldrich or Acros and used as received.

The starting dimethoxy cyclidene [Ni[(MeOEthi)$_2$Me$_2$[15]-tetraeneN$_4$]](PF$_6$)$_2$ and [Ni[(MeNMe$_2$)$_2$Me$_2$[15]tetra-eneN$_4$]](PF$_6$)$_2$ were synthesized according to the published procedure.[58] Dichloropentaethyleneglycol was prepared from pentaethylene glycol and $SOCl_2$ as described by Pedersen.[59] Benzo-[15-crown-5] and benzo-[18-crown-6] were obtained from catechol and dichlorotetraethylene or dichloropentaethylene glycol, respectively, according to the method described by Izatt group.[60]

The diammonium guests were prepared as thiocyanate or perchlorate salts (that have sufficient solubility in organic solvents) after treatment of the corresponding commercial diamines with hydrogen thiocyanate or perchloric acid in ethanol.

NMR spectra were recorded on a Bruker AM-300 spectrometer, IR spectra on a Mattison 1000 FTIR spectrometer, and UV-Vis spectra on a Hitachi U-2000 spectrophotometer. Mass-spectra were measured at Mass Consortium (San Diego, CA) (electrospray ionization) and Mass Spectrometry Service Laboratory at University of Minnesota Department of Chemistry (HRMS). Elemental analyses were performed by Desert Analytics, Tucson, AZ.

NMR titration experiments were carried out according to the procedure described earlier.[23] K_{assoc} values were determined following the proton signals of α-CH_2 group of the diammonium cations and calculated by nonlinear least-squares fit of the titration curve for reversible 1:1 complexation.[61,62] On the basis of repetitive measurements, the estimated error was $<10\%$. The concentration of the diammonium salts (thyocyanates or perchlorates) used for titration with tweezer **1** was 1.0×10^{-2} M, except for trimethylene- and tetramethylenediamonium thiocyanate where 1.0×10^{-3} M solutions were used because of the low solubility of these salts in acetonitrile. All measurements for tweezer **2** were done at 1.0×10^{-3} M concentration of the diammonium salts.

4.2. Synthetic procedures

4.2.1. 4′-Formylbenzo-[15-crown-5]. The compound was synthesized from benzo-15-crown-5 and hexamethylene tetramine as described below using published procedures for obtaining the formyl-derivatives of similar compounds.[63,64] Benzo[15]crown-5 (10.5 g, 39.1 mmol) and hexamethylene tetramine (5.72 g, 41 mmol) were mixed with trifluoroacetic acid (29 ml) under N_2. The reaction mixture was heated to 100°C and kept at this temperature for 24 h. The dark red mixture was cooled to 5°C, mixed with ice (450 g), and stirred for 1 h. The product was extracted with chloroform (4×250 ml), the chloroform layer was dried over magnesium sulfate, filtered, and rotary evaporated. The concentrated residue was loaded on a silica chromatography column (3 cm×25 cm) and eluted with $CHCl_3$/MeOH (2% MeOH). The target product was contained in the first fraction (which has a small yellow tail). Evaporation of the solvent yielded pale-yellow oil, which solidefied upon recrystallization from heptane. Yield 2.5 g (8.4 mmol, 22%). This material was also obtained by the reaction of benzo-15-crown-5 with *N*-methylformanilide according to the procedure described by Hyde et al.[65] in 26% yield, and from dichlorotetraethylene glycol and catechol by method described by Wu and co-workers[60] in 16% yield. ^{1}H NMR ($CHCl_3$-*d*): δ 9.83 (s, 1H), 7.43 (dd, *J*=6, 1.3 Hz, 1H), 7.37 (d, *J*=1.3 Hz), 6.93 (d, *J*=6 Hz, 1H), 4.22–4.15 (m, 4H), 3.96–3.89 (m, 4H), 3.77–3.74 (m, 8H).

4.2.2. 4′-Formylbenzo-[18-crown-6]. The compound was obtained form benzo-18-crown-6 according to a modified procedure described by Hyde et al.[65] with a work up adapted from Shuying.[66] After extraction of the crude product into chloroform and removing the solvent under reduced pressure, the residual brown oil was dissolved in small amount of dichloromethane and mixed with a suitable amount of Al_2O_3 (neutral) to get a caramel-like oil. The extraction of the material was done by treatment of the mixture with hot Et_2O. After cooling the ether solution in the freezer, the product crystallized as white needles (55% yield). ^{1}H NMR ($CHCl_3$-*d*): δ 9.86 (s, 1H), 7.44 (dd, *J*=8, 1.8 Hz, 1H), 7.40 (d, *J*=1.8 Hz, 1H), 6.94 (d, *J*=8 Hz, 1H), 4.26–4.20 (m, 4H), 3.96–3.90 (m, 4H), 3.80–3.71 (m, 8H), 3.69 (s, 4H); ^{13}C NMR ($CHCl_3$-*d*): δ 191.4, 154.8, 130.5, 127.3, 112.3, 111.5, 71.4, 71.3, 71.2, 71.1, 71.0, 69.7, 69.6, 69.4, 69.3.

4.2.3. 4′-Hydroxymethylbenzo-[15-crown-5]. The compound was obtained by reduction of the formyl-derivative using a modified procedure described by Hyde et al.[65] 4′-Formylbenzo[15-crown-5] (2.5 g, 8.5 mmol) was suspended in 26 ml of absolute ethanol, and the mixture was cooled to 0°C. Sodium borohydride (0.32 g, 8.5 mmol) was added to this suspension in small portions, maintaining the temperature below 7°C. After the addition of sodium borohydride, the mixture was stirred at 0°C for 1 h 40 min, and then the solvent was rotary evaporated. The residue was washed with brine and extracted with methylene chloride (3×30 ml). The combined extracts were dried over magnesium sulfate, filtered, and rotary evaporated, yielding 2.4 g (8.1 mmol, 95%) of an oily product. ^{1}H NMR ($CHCl_3$-*d*): δ 6.89 (d, *J*=1.4 Hz, 1H), 6.85 (dd, *J*=6, 1.4 Hz, 1H), 6.80 (d, *J*=6 Hz, 1H), 4.57 (m, 2H), 4.10 (m, 4H), 3.90(m, 4H), 3.75 (m, 8H), 2.50 (br.s, 1H).

4.2.4. (4′)-Hydroxymethylbenzo-[18-crown-6]. The compound was synthesized using the same method as described above for the B15C5-derivative, starting with 3.2 g (9.4 mmol) of 4′-formylbenzo-[18-crown-6], 0.34 g of

$NaBH_4$, and 30 ml of EtOH. After solvent evaporation, residue was not treated with brine, but was washed with water instead, and extracted with CH_2Cl_2 (3×30 ml). Yield: 2.7 g (7.9 mmol, 84%). ^{1}H NMR ($CHCl_3$-*d*): δ 6.95 (d, *J*=1.7 Hz, 1H), 6.89 (dd, *J*=8.1, 1.7 Hz, 1H), 6.82 (d, *J*=8.1 Hz, 1H), 4.62 (s, 2H), 4.20–4.13 (m, 4H), 4.00–3.95 (m, 4H), 3.8–3.76 (m, 4H), 3.72–3.70 (m, 4H), 3.68 (s, 4H), 2.66 (br.s. 1H). ^{13}C NMR ($CHCl_3$-*d*): δ 149.4, 148.6, 135.0, 120.2, 114.4, 113.4, 71.2, 71.1, 70.0, 69.6, 69.5, 69.3, 65.3. *m/z* (ESMS): 341 ([M−H]$^-$), 343 ([MH]$^+$). Anal. calcd for $C_{17}H_{26}O_7$: C, 59.64; H, 7.65; found: C, 58.69; H, 7.77.

4.2.5. 4′-Chloromethylbenzo-[15-crown-5]. The compound was prepared by modification of known procedures.[67,68] Hydroxymethylbenzo-[15-crown-5] (2.5 g, 8.4 mmol) was dissolved in 150 ml of methylene chloride, and fine powder of potassium carbonate (3.39 g, 24.5 mmol) was added. The mixture was cooled to 0°C under N_2, and thionyl chloride (1.13 ml, 16 mmol) was added. The reaction was stirred for 45 min, then filtered, and the solvent was removed on a rotary evaporator, yielding 2.91 g of the semi-solid product, which was used without further purification. *m/z* (ESMS): 318 ([MH]$^+$), 356 ([M+K]$^+$).

4.2.6. 4′-Chloromethylbenzo-[18-crown-6]. The compound was obtained using the same procedure as above for the B15C5-derivative, starting with 4′-hydroxymethylbenzo-[18-crown-6] (2.7 g, 7.9 mmol), CH_2Cl_2 (170 ml), K_2CO_3 (3.60 g, 26.1 mmol), and $SOCl_2$ (2.07 g, 17.4 mmol). Yield: 2.55 g (7.07 mmol, 90%). ^{1}H NMR ($CHCl_3$-*d*): δ 6.91 (m, 2H), 6.80 (d, *J*=8.0 Hz, 1H), 4.61 (s, 2H), 4.23–4.15 (m, 4H), 4.00–3.92 (m, 4H), 3.79–3.75 (m, 4H), 3.73–3.68 (m, 12H). ^{13}C NMR ($CHCl_3$-*d*): δ 148.8, 144.5, 130.7, 121.8, 115.1, 113.3, 70.9, 70.8, 69.5, 68.9, 63.5, 46.7. FT-IR (KBr): ν 3377, 2903, 1650, 1597, 1520, 1455, 1425, 1271, 1182, 1129, 1099, 993, 957, 844, 812, 718, 692, 609. *m/z* (ESMS): 361 ([MH]$^+$), 399 ([M+K]$^+$). HRMS: calcd for $C_{17}H_{25}O_6Cl$ [M$^+$]: 360.1340, found: 360.1361.

4.2.7. Phthalimidomethylbenzo-[15-crown-5]. Chloromethylbenzo-[15-crown-5] (2.8 g, 8.8 mmol) and potassium phthalimide (1.8 g, 9.7 mmol) were mixed with 30 ml of dimethylformamide and heated at 90°C for 1 h. The reaction mixture was cooled, 60 ml of chloroform were added, and the mixture was poured into 250 ml of water. The chloroform layer was separated, and the aqueous layer was extracted with an additional amount of chloroform (2×200 ml). The combined chloroform extracts were washed with 0.15 M NaOH (2×400 ml), and with water (4×500 ml). The chloroform extract was dried over magnesium sulfate, filtered, and rotary evaporated, yielding 3 g of an oily product, which was recrystallized from 30 ml of ethanol. Yield: 1.85 g (4.32 mmol, 91%). ^{1}H NMR ($CHCl_3$-*d*): δ 7.84–7.80 (m, 2H), 7.70–7.66 (m, 2H), 7.0–6.96 (m, 2H), 6.77 (d, *J*=6.3, 1H), 4.74 (s, 2H), 4.13–4.10 (m, 2H), 4.09–4.06 (m, 2H), 3.89–3.84 (m, 4H), 3.72 (s, 8H). ^{13}C NMR ($CHCl_3$-*d*): δ 168.5, 149.5, 149.2, 134.4, 132.5, 130.0, 123.7, 122.3, 115.1, 114.3, 71.5, 70.9, 70.0, 69.5, 69.4, 41.8. FT-IR (KBr): ν 3432, 2948, 2874, 1769, 1715, 1611, 1514, 1469, 1436, 1394, 1337, 1266, 1141, 991, 941, 756, 725, 665, 528. HRMS: calcd for $C_{23}H_{25}NO_7$ [M$^+$]: 427.1631, found: 427.1624.

4.2.8. Phthalimidomethylbenzo-[18-crown-6]. The compound was obtained by the procedure described above, starting with chloromethylbenzo-[18-crown-6] (2.55 g, 7.07 mmol), potassium phthalimide (1.39 g, 7.50 mmol) in 24 ml of DMF. Yield: 2.2 g (4.67 mmol, 66%). ^{1}H NMR ($CHCl_3$-*d*): δ 7.86–7.83 (m, 2H), 7.73–7.70 (m, 2H), 7.00–6.97 (m, 2H), 6.80 (d, *J*=8.7 Hz, 1H), 4.74 (s, 2H), 4.13–4.10 (m, 2H), 4.09–4.06 (m, 2H), 3.89–3.84 (m, 4H), 3.72 (s, 8H). ^{13}C NMR ($CHCl_3$-*d*): δ 168.5, 149.4, 134.4, 132.6, 130.0, 123.7, 122.3, 115.3, 114.6, 71.3, 71.2, 70.0, 69.6, 41.8.). FT-IR (KBr): ν 3450, 2922, 2876, 1773, 1717, 1616, 1520, 1469, 1436, 1396, 1352, 1262, 1127, 991, 961, 746, 723, 658, 531. *m/z* (ESMS): 472 ([MH]$^+$), 494 ([M+Na]$^+$). Anal. calcd for $C_{25}H_{29}NO_6$: C, 63.68, H, 6.20, N 2.97; found: C, 63.70, H, 6.07, N 2.66.

4.2.9. 4′-Aminomethylbenzo-[15-crown-5].[69] The phthalimide derivative of 4-methylbenzo-[15-crown-5] (1.5 g, 3.5 mmol) was dissolved in 45 ml of hot ethanol. To this solution, 0.45 g (14 mmol) of anhydrous hydrazine in 15 ml of ethanol was added, and the reaction mixture was refluxed for 2 h. The reaction mixture was cooled on an ice bath and filtered, the precipitate of phtalhydrazide was washed with ice-cold ethanol. The combined filtrates were rotary evaporated, producing 1.2 g of crude off-white semi-crystalline solid. The residue was washed with chloroform; and undissolved solid residue was discarded. The chloroform filtrate was rotary evaporated to a final volume of about 20 ml, and refrigerated for several hours. An additional amount of solid phthalhydrazide formed was separated by filtration, and the solvent was removed by rotary evaporation. The residue was treated with 20 ml of hot acetonitrile and filtered. Evaporation of the solvent resulted in transparent yellow oil of the product. Yield: 0.98 g (3.4 mmol, 50%). ^{1}H NMR ($CHCl_3$-*d*), δ: 6.85–6.81 (m, 3H), 4.15–4.10 (m, 4H), 3.90–3.88 (m, 4H), 3.78 (s, 2H), 3.74 (s, 8H). ^{13}C NMR ($CHCl_3$-*d*), δ: 149.3; 148.0; 136.6 119.8; 114.3; 113.3; 71.1; 70.5; 69.7; 69.3, 69.1; 46.1.

4.2.10. 4′-Aminomethylbenzo-[18-crown-6]. The compound was synthesized according to the procedure above, using phtalimidomethylbenzo-[18-crown-6] (1.9 g, 4.0 mmol), 50 ml of hot EtOH, and 0.513 g (16.0 mmol) of anhydrous hydrazine. Yield: 1.19 g (3.49 mmol, 87%). ^{1}H NMR (CH_3Cl-d_3): δ 6.88–6.82 (m, 3H), 4.18–4.11 (m, 4H), 3.94–3.86 (m, 4H), 3.80 (s, 2H), 3.78–3.72 (m, 8H), 3.69 (s, 4H), 1.98 (br.s, 2H). ^{13}C NMR ($CHCl_3$-*d*): δ 149.1; 148.0; 135.3 120.5; 114.4; 113.7; 71.15; 71.11; 71.05; 71.01; 70.0; 69.4, 69.3; 46.1. *m/z* (ESMS): 340 ([M−H]$^-$), 342 ([MH]$^+$). HRMS: calcd for $C_{17}H_{27}NO_6Na$ [M+Na]$^+$: 364.1736, found: 364.1731.

4.2.11. [Ni[(4′-aminonomethylbenzo-[15-crown-5])$_2$-Me$_2$[15]tetraeneN$_4$]](PF$_6$)$_2$ (tweezer 1/host 1). Bis-methoxy Ni[15]Jäger (PF_6)$_2$ (0.4 g, 0.6 mmol) was dissolved in 10 ml of acetonitrile and mixed with a solution of 4′-aminomethylbenzo-[15-crown-5] (0.5 g, 1.7 mmol) in 10 ml of acetonitrile. The reaction mixture gradually turned red. After 10 min, the acetonitrile was removed on a rotary evaporator at room temperature, leaving a red film. The film was dissolved in 50 ml of boiling methanol. Upon cooling to ambient temperature, some oil was deposited. The mixture was decanted from the oil and cooled on ice, yielding orange

crystalline precipitate. The precipitate was filtered, immediately washed with diethyl ether and dried. The yield of this fraction was 0.15 g. Additional amount of the product was isolated from the oily material deposited from methanol. The material was dissolved upon heating in the filtrate obtained in the above workup, and the mixture was cooled on ice. A semi-crystalline solid was filtered and immediately washed with ether, yielding 0.28 g of the product. Both fractions (0.43 g, (0.35 mmol, 62%) gave identical spectra. ^{1}H NMR ($CHCl_3$-*d*): δ 7.65 (s, 2H), 6.96–6.92 (m, 6H), 4.61 (s, 4H), 4.07–4.05 (m, 8H), 3.81–3.77 (m, 8H), 3.65–3.61 (m, 20H), 3.24 (m, 4H), 2.34 (s, 6H), 2.16 (s, 6H), 1.86 (m, 2H). UV–Vis (CH_3CN) λ_{max} (log ε) 480 (3.15), 382 (4.62), 284 (4.45) nm. FT-IR (KBr): ν 3430, 3262, 2932, 2875, 1571, 1519, 1450, 1390, 1350, 1268, 1134, 1052, 941, 844, 560, 521. *m/z* (ESMS): 1223 ($[M-H]^-$), 1369 ($[M+PF_6]^-$), 1079 ($[M-PF_6]^+$), 933 ($[M-PF_6-HPF_6]^+$). Anal. calcd for $NiC_{47}H_{66}N_6O_{10}P_2F_{12}$: C, 46.06; H, 5.59; N, 6.86; found: C, 46.10; H, 5.81; N, 6.50.

4.2.12. [Ni[(4′-aminomethylbenzo-[18-crown-6])$_2$Me$_2$[15]-tetraeneN_4]](PF$_6$)$_2$ (tweezer 2/host 2). The compound was obtained using the procedure for synthesis of B15C5 derivative as described above, starting with bis-methoxy Ni[15]Jäger $(PF_6)_2$ (0.83 g, 1.19 mmol) in CH_3CN (20 ml), and 4-aminomethylbenzo-[18-crown-6] (1.18 g, 3.46 mmol) in CH_3CN (10 ml). Yield 0.95 g (0.72 mmol, 61%). ^{1}H NMR (CH_3CN-d_3): 7.60 (s, 2H), δ 2.17 (s, 8H), 2.32 (s, 6H), 3.23 (m, 4H), 3.35 (s, 8H), 3.58 (m, 20H), 3.73 (m, 8H), 4.14 (m, 8H), 4.60 (s, 4H), 6.91 (m, 4H), 7.05 (s, 2H). ^{13}C NMR (CH_3CN-d_3): δ 172.2, 167.3, 158.3, 149.6, 149.3, 129.3, 122.1, 113.8, 113.3, 111.3, 71.5, 71.4, 71.3, 70.0, 69.0, 60.0, 50.6, 48.0, 26.5, 20.3, 18.1. FT-IR (KBr): ν 3440, 3244, 2913, 1570, 1521, 1457, 1387, 1351, 1266, 1125, 1097, 1061, 955, 849, 561, 522. *m/z* (ESMS): 1312 ($[M-H]^-$), 1459 ($[M+PF_6]^-$), 1022 ($[M-H-2PF_6]^+$). Anal. calcd for $NiC_{51}H_{76}N_6O_{12}P_2F_{12}\cdot 0.5Et_2O$: C, 47.12; H, 6.04; N, 6.22; found: C, 47.57; H, 5.98; N, 6.46.

Acknowledgements

This work was supported by Tufts University (startup funds and Faculty Research Award to E. R. A.). We thank Paul Filson for exploring alternative ways of the preparation of functionalized benzocrowns.

References

1. Lehn, J.-M. *Supramolecular Chemistry: Concepts and Perspectives*. VCH: Weinheim, 1995.
2. Bianchi, A.; Bowman-James, K.; Garcia-Espana, E. In *Supramolecular Chemistry of Anions*. Bianchi, A., Bowman-James, K., Garcia-Espana, E., Eds.; Wiley/VCH: New York, 1997.
3. Hartley, J. H.; James, T. D.; Ward, C. J. *J. Chem. Soc., Perkin Trans. 1* **2000**, 3155–3184.
4. Rybak-Akimova, E. V. *Rev. Inorg. Chem.* **2001**, *21*, 207–298.
5. Busch, D. H. *Chem. Rev.* **1993**, *93*, 847–860.
6. Fabbrizzi, L.; Poggi, A. In *Transition Metals in Supramolecular Chemistry*. Fabbrizzi, L., Poggi, A., Eds.; Kluwer Academic: Dordrecht, 1994.
7. Canary, J. W.; Gibb, B. C. *Progr. Inorg. Chem.* **1997**, *45*, 1–82.
8. Busch, D. H. *Pure Appl. Chem.* **1980**, *52*, 2477–2484.
9. Busch, D. H.; Alcock, N. W. *Chem. Rev.* **1994**, *94*, 585–623.
10. Kolchinski, A. G.; Korybut-Daszkiewicz, B.; Rybak-Akimova, E. V.; Busch, D. H.; Alcock, N. W.; Clase, H. J. *J. Am. Chem. Soc.* **1997**, *119*, 4160–4171.
11. Rybak-Akimova, E. V.; Kuczera, K.; Jas, G. S.; Deng, Y.; Busch, D. H. *Inorg. Chem.* **1999**, *38*, 3423.
12. Rybak-Akimova, E. V.; Kuczera, K. *Inorg. Chem.* **2000**, *39*, 2462–2472.
13. Breslow, R.; Yang, J.; Yan, J. M. *Tetrahedron* **2002**, *58*, 653–659.
14. Belvedere, S.; Breslow, R. *Bioorg. Chem.* **2001**, *29*, 321–331.
15. Yang, J.; Breslow, R. *Tetrahedron Lett.* **2000**, *41*, 8063–8067.
16. Yang, J.; Weinberg, R.; Breslow, R. *Chem. Commun.* **2000**, 531–532.
17. Breslow, R.; Dong, S. D. *Chem. Rev.* **1998**, *98*, 1997–2011.
18. Breslow, R.; Gabriele, B.; Yang, J. *Tetrahedron Lett.* **1998**, *39*, 2887–2890.
19. Breslow, R. *Acc. Chem. Res.* **1995**, *28*, 146–153.
20. French, R. R.; Holzer, P.; Leuenberger, M.; Nold, M. C.; Woggon, W.-D. *J. Inorg. Biochem.* **2002**, *88*, 295–304.
21. Woggon, W.-D.; Wagenknecht, H.-A.; Claude, C. *J. Inorg. Biochem.* **2001**, *83*, 289–300.
22. French, R. R.; Holzer, P.; Leuenberger, M. G.; Woggon, W.-D. *Angew. Chem., Int. Ed.* **2000**, *39*, 1267–1269.
23. Kryatova, O. P.; Kolchinskii, A. G.; Rybak-Akimova, E. V. *J. Inclusion Phenom. Macrocycl. Chem.* **2002**, *42*, 251–260.
24. Izatt, R. M.; Pawlak, K.; Bradshaw, J. S.; Bruening, R. L. *Chem. Rev.* **1991**, *91*, 1721–2085.
25. Tsubaki, K.; Nuruzzaman, M.; Kusumoto, T.; Hayashi, N.; Wang, B.-G.; Fuji, K. *Org. Lett.* **2001**, *3*, 4071–4073.
26. Tsubaki, K.; Tanaka, H.; Furuta, T.; Kinoshita, T.; Fuji, K. *Tetrahedron Lett.* **2000**, *41*, 6089–6093.
27. Fuji, K.; Tsubaki, K.; Tanaka, K.; Hayashi, N.; Otsubo, T.; Kinoshita, T. *J. Am. Chem. Soc.* **1999**, *121*, 3807–3808.
28. Prevot-Halter, I.; Weiss, J. *New J. Chem.* **1998**, 869–874.
29. Jeong, K.; Park, J. W.; Cho, Y. L. *Tetrahedron Lett.* **1996**, *37*, 2795–2798.
30. Goodman, M. S.; Jubian, V.; Linton, B.; Hamilton, A. D. *J. Am. Chem. Soc.* **1995**, *117*, 11610–11611.
31. Gunter, M. J.; Johnston, M. R. *Tetrahedron Lett.* **1992**, *33*, 1771–1774.
32. Fages, F.; Desvergne, J. P.; Kampke, K.; Bouas-Laurent, H.; Lehn, J. M.; Meyer, M.; Albrecht-Gary, A. M. *J. Am. Chem. Soc.* **1993**, *115*, 3658–3664.
33. Smeets, J. W. H.; Sijbesma, R. P.; Van Dalen, L.; Spek, A. L.; Smeets, W. J. J.; Nolte, R. J. M. *J. Org. Chem.* **1989**, *54*, 3710–3717.
34. Hamilton, A.; Lehn, J. M.; Sessler, J. L. *J. Am. Chem. Soc.* **1986**, *108*, 5158–5167.
35. Jones, N. F.; Kumar, A.; Sutherland, I. O. *J. Chem. Soc., Chem. Commun.* **1981**, 990–992.
36. Mageswaran, R.; Mageswaran, S.; Sutherland, I. O. *J. Chem. Soc., Chem. Commun.* **1979**, 722–724.
37. Johnson, M. R.; Sutherland, I. O.; Newton, R. F. *J. Chem. Soc., Chem. Commun.* **1979**, 306–308.
38. Johnson, M. R.; Sutherland, I. O.; Newton, R. F. *J. Chem. Soc., Chem. Commun.* **1979**, 309–311.

39. Schammel, W. P.; ZImmer, L. L.; Busch, D. H. *Inorg. Chem.* **1980**, *19*, 3159–3167.
40. Horwitz, C. P.; Navarro, R.; Dailey, G. C. *Inorg. Chem.* **1990**, *29*, 4262–4268.
41. Takeuchi, K. J.; Busch, D. H.; Alcock, N. W. *J. Am. Chem. Soc.* **1983**, *105*, 4261–4270.
42. Meade, T. J.; Alcock, N. W.; Busch, D. H. *Inorg. Chem.* **1990**, *29*, 3766–3776.
43. Cameron, J. H.; Scott, E. L. *J. Chem. Soc., Dalton Trans.* **1995**, 1029–1034.
44. Nazarenko, A. Y.; Robinson, P. D.; Wilson, R. M.; Kolchinski, A. G.; Disch, J. S.; Rybak-Akimova, E. V. *J. Inclusion Phenom. Macrocyclic. Chem.* **2002**, *42*, 83–87.
45. Meade, T. J.; Fendrick, C. M.; Padolik, P. A.; Cottrell, C. E.; Busch, D. H. *Inorg. Chem.* **1987**, *26*, 4252–4257.
46. Cameron, J. H.; Clarke, C. A.; Rosair, G.; Scott, E. L. *Coord. Chem. Rev.* **1998**, *174*, 313–326.
47. Cameron, J. H.; Graham, S. *J. Chem. Soc., Dalton Trans.* **1989**, 1599–1608.
48. Jayathirtha, Y.; Krishnan, V. *Indian J. Chem. Sect. A* **1979**, *18A*, 311–314.
49. Barboiu, M. D.; Hovnanian, N. D.; Luca, C.; Cot, L. *Tetrahedron* **1999**, *55*, 9221–9232.
50. Connors, K. A. *Binding Constants: The measurement of the Molecular Complex Stability*. Wiley: New York, 1987.
51. Strakhova, N. N.; Solov'ev, V. P.; Raevskii, O. A. *Koord. Khim.* **1989**, *15*, 483–485.
52. Izatt, R. M.; Bradshaw, J. S.; Nielsen, S. A.; Lamb, J. D.; Christensen, J. *J. Chem. Rev.* **1985**, *85*, 271–339.
53. Izatt, R. M.; Wang, T.; Hathaway, J. K.; Zhang, X. X.; Curtis, J. C.; Bradshaw, J. S.; Zhu, C. Y.; Huszthy, P. *J. Inclusion Phenom. Mol. Recognit. Chem.* **1994**, *17*, 157–175.
54. Lin, W.-K.; Alcock, N. W.; Busch, D. H. *J. Am. Chem. Soc.* **1991**, *113*, 7603–7608.
55. Timko, J. M.; Moore, S. S.; Walba, D. M.; Hiberty, P. C.; Cram, D. J. *J. Am. Chem. Soc.* **1977**, *99*, 4207–4219.
56. Trueblood, K. N.; Knobler, C. B.; Lawrence, D. S.; Stevens, R. V. *J. Am. Chem. Soc.* **1982**, *104*, 1355–1362.
57. Doxsee, Jr., K. M.; F, P. E.; Weakley, T. J. R. *Tetrahedron* **2000**, *56*, 6683–6691.
58. Cairns, C. J.; Busch, D. H. *Inorg. Synth.* **1990**, *27*, 261.
59. Pedersen, C. J. *J. Am. Chem. Soc.* **1967**, *89*, 7017–7036.
60. Wu, Y.; An, H.; Tao, J.; Bradshaw, J. S.; Izatt, R. M. *J. Inclusion Phenom.* **1990**, *9*, 267–274.
61. Sahai, R.; Loper, G. L.; Lin, S. H.; Eyring, H. *Proc. Natl Acad. Sci. USA* **1974**, *71*, 1499–1503.
62. Fielding, L. *Tetrahedron* **2000**, *56*, 6151–6170.
63. Wada, F.; Hirayama, H.; Namiki, H. *Bull. Chem. Soc. Jpn* **1980**, *53*, 1473–1474.
64. Zhilina, Z. I.; Mel'nik, V. I.; Andronati, S. A.; Dmitrieva, T. N.; Ganevich, V. N. *Zh. Org. Khim.* **1989**, *25*, 1070–1075.
65. Hyde, E. M.; Shaw, B. L.; Shepherd, I. *J. Chem. Soc., Dalton Trans.* **1978**, 1696–1705.
66. Shuying, T.; Yuting, W.; Changhong, P. *Huaxue Shiji* **2000**, *22*, 49–51.
67. Haines, A. H.; Hodgkisson, I.; Smith, C. *J. Chem. Soc., Perkin Trans. 1* **1983**, 311–318.
68. Howell, S. J.; Spencer, N.; Philp, D. *Tetrahedron* **2001**, *57*, 4945–4954.
69. Oe, T.; Morita, M.; Toyo'oka, T. *Anal. Sci.* **1999**, *15*, 1021–1023.
70. Gokel, G. W.; Goli, D. M.; Minganti, C.; Echegoyen, L. *J. Am. Chem. Soc.* **1983**, *105*, 6786–6790.
71. Izatt, R. M.; Lamb, J. D.; Izatt, N. E.; Rossiter, B. E. J.; Christensen, J. J.; Haymore, B. L. *J. Am. Chem. Soc.* **1979**, *101*, 6273–6276.