Synthesis of 1,10-Disubstituted 1,4,7,10,13,16-Hexaazacyclooctadecanes and Their Extractability for Metal Cations

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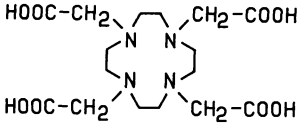
1,10-Disubstituted 1,4,7,10,13,16-hexaazacyclooctadecanes (hexaaza-18-crowns) having lipophilic groups were synthesized from 1,2-ethanediamine as a starting material. Cyclization of 3,6-ditosyl-3,6-diazaoctanedioyl dichloride and 3,6-ditosyl-3,6-diazaoctane-1,8-diamine under the high dilution conditions, followed by diborane reduction of the amide carbonyl, gave the macrocyclic precursor. A series of reactions, i.e., acylation, diborane reduction, and detosylation, afforded 1,10-disubstituted hexaaza-18-crowns. Their extractability for metal cations was examined by spectrophotometric analysis. They showed relatively high extractability for Ag^+, Zn^{2+}, and Cd^{2+}.

An understanding of the underlying factors for metal ion recognition by organic substrates is important in wide-ranging ramifications, especially in the areas of chemistry and biochemistry. Cyclic ligands can be further "tuned" by adjusting the macrocyclic hole-size until an optimum fit is achieved for a metal ion of interest. Such macrocyclic hole-size variation is considerably interest, and many studies of this type are directed to cyclic polyether ligands and typical metal ions.[1] Recently, similar studies directed to transition metal ions have received attention.[2] Further, by introducing additional ligating groups into a macrocycle its properties can be modified, so that its specificity in metal ion binding increases and/or its solubility changes.[3]

Macrocyclic polyamines have been synthesized and their binding properties toward metal cations are described; most of the works concern tetraaza-12(or 14)-membered ring systems.[4] For example, 12-membered **1** gives stable alkali and alkaline earth metal ion complexes[5] whereas the unsubstituted ligand binds only transition metal ions. Macrocycle **2**, of which a long lipophilic side chain makes the ligand and its metal ion complex soluble in organic solvents, can be used in extraction of metal ions from an aqueous solution to an organic phase.[6]

Tetraazamacrocyclic ligands containing a single pendant-arm have been synthesized based on template methods.[7] Macrobicyclic polyamines are also synthesized by a sequential two-step pathway[8] or by direct macrobicyclization via tripode–tripode coupling reaction.[9] But, there is no report on the selective introduction of two lipophilic groups in 1,4,7,10,13,16-hexaazacyclooctadecane (hexaaza-18-crown) at the symmetrical, e.g., 1,10-positions. Here we report the synthesis and extractability of macrocyclic polyamines, which are characterized by the parent azacrown ring and "arms".



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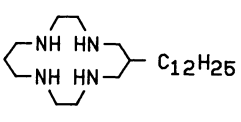

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Results and Discussion

Synthesis of 1,10-Disubstituted Hexaaza-18-crowns. According to the literature,[10] 3,6-ditosyl-3,6-diazaoctanedioyl dichloride (**6**) was prepared from 1,2-ethanediamine via 1,2-bis(tosylamino)ethane (**3**), dimethyl 3,6-ditosyl-3,6-diazaoctanedioate (**4**) and then 3,6-ditosyl-3,6-diazaoctanedioic acid (**5**). The melting point of **6** was lower than that in the literature[10b] by 100 °C, but the structure of **6** was confirmed by IR and ^1H NMR spectra, and elemental analysis.

Diacid dichloride **6** was treated with excess liquid ammonia in dichloromethane to give the corresponding diamide **7** in 77% yield, which was converted into 3,6-ditosyl-3,6-diazaoctane-1,8-diamine (**8**) by the reduction with diborane (64% yield). Cyclization of **6** and **8** in dichloromethane under the high dilution conditions in the presence of triethylamine as a condensing agent gave cyclic diamide, 4,7,13,16-tetratosyl-1,4,7,10,13,16-hexaazacyclooctadecane-2,9-dione (**9**) in 50% yield. The macrocyclic precursor, 1,4,10,13-tetratosyl-1,4,7,10,13,16-hexaazacyclooctadecane (**10**) was obtained by reduction of **9** with diborane in 56% yield. 1,10-Dialkyl-4,7,13,16-tetratosyl-1,4,7,10,13,16-hexaazacyclooctadecanes (**12a, b**) were synthesized by acylation with benzoyl chloride and octanoyl chloride, respectively, in the presence of triethylamine in dichloromethane, followed by the reduction with diborane.

Hydrolysis with hydrogen bromide in acetic acid in the presence of phenol and reductive elimination with lithium aluminium hydride are known to be effective for detosylation of *N*-tosylated amine derivatives. But, detosylation of **12** by these reagents gave

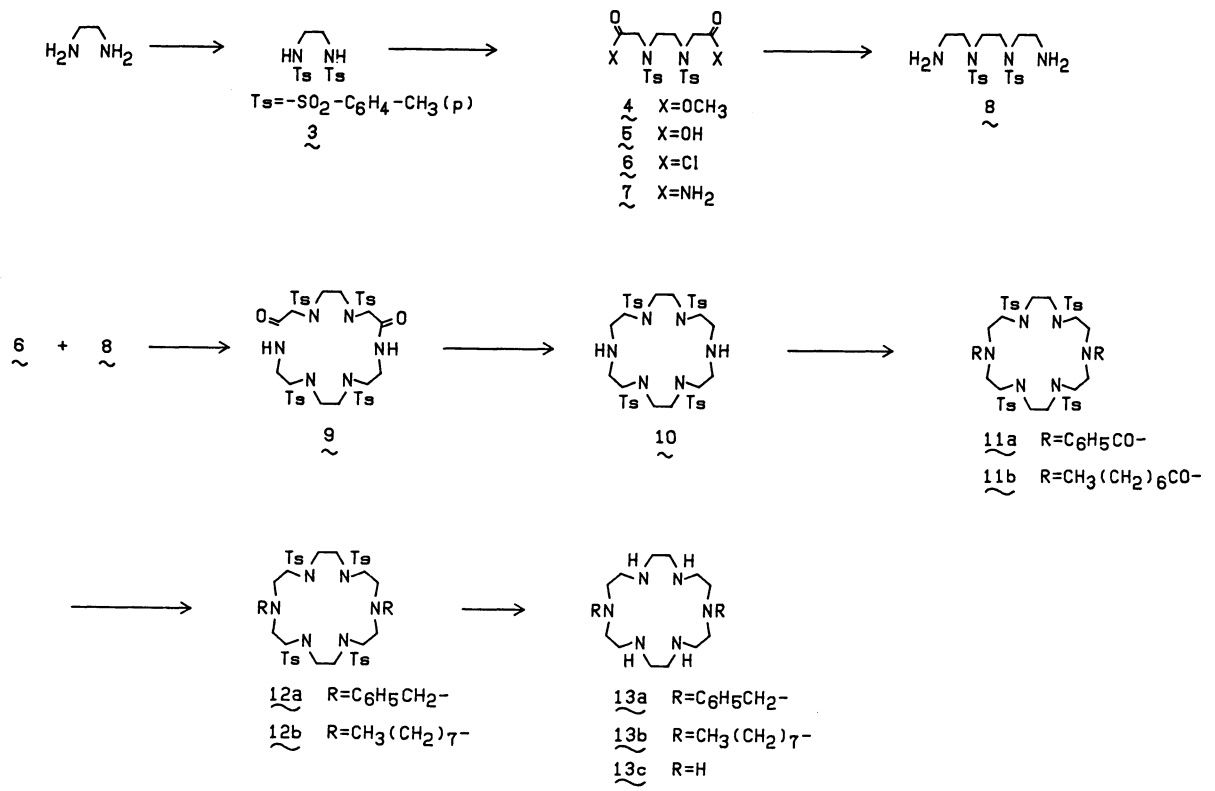

Table 1. Extractability of Hexaaza-18-crowns for Metal Cations

R%[a]	Li^+	Na^+	K^+	Ca^{2+}	Ba^{2+}
$PhCH_2$	14.8	13.0	14.4	15.7	16.1
C_8H_{17}	16.1	14.8	17.5	21.3	26.2
H	8.8	8.1	8.9	9.3	5.4

R%[b]	Li^+	Na^+	K^+	Rb^+	Cs^+	Mg^{2+}	Ca^{2+}	Ba^{2+}
$PhCH_2$	15.2	15.9	18.3	20.1	16.6	15.7	17.7	19.6
C_8H_{17}	18.9	19.3	21.7	23.1	21.0	18.9	21.4	23.4
H	5.0	4.2	3.9	2.4	2.9	3.7	8.5	4.6

R%[b]	Cu^+	Ag^+	Cu^{2+}	Zn^{2+}	Cd^{2+}	Fe^{3+}	Co^{2+}	NH_4^+
$PhCH_2$	22.5	43.4	22.4	39.8	36.4	19.7	27.1	23.3
C_8H_{17}	27.9	39.4	25.8	37.6	41.7	21.3	28.2	23.0
H	4.5	13.7	4.9	12.2	13.4	5.7	6.2	1.6

Conditions: a) [crown]=5×10^{-5} M (1 M=1 mol dm^{-3}), [MOH]=5×10^{-5} M, [$M(OH)_2$]=2.5×10^{-5} M, [picric acid]=5×10^{-5} M. b) [crown]=5×10^{-5} M, [MCl]=5×10^{-5} M, [MCl_2]=2.5×10^{-5} M, [MCl_3]=1.7×10^{-5} M, except for Ag^+~[$AgNO_3$]=5×10^{-5} M and Mg^{2+}~[$MgSO_4$]=2.5×10^{-5} M, [NaOH]=5×10^{-5} M, [picric acid]=5×10^{-5} M.

only complex mixtures. Finally, hydrolysis with concd. sulfuric acid at about 100 °C was found to be effective, giving 1,10-dialkyl-1,4,7,10,13,16-hexaazacyclooctadecane (1,10-disubstituted hexaaza-18-crown) (**13a, b**) in moderate yields.

Extractability. Metal cation-binding property of 1,10-disubstituted hexaaza-18-crowns **13a, b** and unsubstituted **13c** was investigated by equilibrating a dichloromethane solution of **13** with an aqueous solution of metal picrate, which was chosen as a metal cation source, at 25 °C. The results on the extraction of metal picrates with **13** are summarized in Table 1.

Metal picrates could not be extracted into a dichloromethane phase in the absence of **13**. Then, metal picrates may be extracted by the interaction with **13**, and the degree of extraction into a dichloromethane phase would reflect the cation-binding ability of **13**.

As shown in Table 1, **13a** and **13b** exhibited enhanced extraction efficiency compared with **13c**.

For alkali metal and alkaline earth metal cations the orders of the extractability of **13a** and **13b** were $Rb^+>K^+>Cs^+\geqq Na^+\simeq Li^+$ and $Ba^{2+}>Ca^{2+}>Mg^{2+}$, while unsubstituted **13c** exhibited metal cation selectivity in the orders of $Li^+\simeq Na^+\simeq K^+>Cs^+\simeq Rb^+$ and $Ca^{2+}>Ba^{2+}>Mg^{2+}$. On the other hand, the size of hexaaza-18-crown ring was found to be almost equal to that of 1,4,7,10,13,16-hexaoxacyclooctadecane (18-crown-6) on the basis of the structural analysis using CPK molecular models. The cation selectivities of 18-crown-6 are $Ba^{2+}>Ca^{2+}>Mg^{2+}$ and $K^+>Na^+$ and are well explained on the basis of the cation size vs. the cavity size correlation.[11] Then, the difference in extractability between **13a, b** and **13c**, which have the same binding site structure, and between **13** and 18-crown-6, which have similar ring size to each other, indicates that both of the side arms and the heteroatoms in the macrocycle play an important role in the incorporation of cations into the cavity of **13** and in the extraction to the organic phase.

The extractability of **13a** and **13b** for transition metal cations was higher than that for typical metal cations. The similar tendency was obtained for **13c**. This phenomenon can be explained by hard soft acid base principle; rather soft nitrogen atom has stronger affinity toward soft transition metal cations than hard typical metal cations. It is noticeable that **13** shows relatively high extractability for Ag^+, Zn^{2+}, and Cd^{2+}.

In most cases, the extractability of dioctylated hexaaza-18-crown **13b** for metal cations was a little higher than that of dibenzylated hexaaza-18-crown **13a**. Octyl group is probably more flexible and lipophilic than benzyl group. Then, **13b** would be liable to incorporate metal cations and its metal cation complexes would be more soluble in the organic phase in comparison with **13a**. The distinct reverse tendency in Ag^+ would result from π-interaction of Ag^+ with phenyl group in **13a**.

These 1,10-disubstituted hexaaza-18-crowns would wrap around the guest cations in such a way that the arms provide axial capping of the guest cations coordinated with the parent hexaaza-18-crown ring. The mobility of the arms attached to hexaaza-18-crown ring may permit dynamic complexation and decomplexation.

Experimental

Measurement. All melting points were measured on a Laboratory Devices MEL-TEMP apparatus and are uncorrected. IR spectra were recorded on a JASCO IR-810 spectrometer. ^1H NMR spectra were recorded on a Hitachi R-40 spectrometer in $CDCl_3$ or DMSO-d_6 using TMS as an internal standard. UV spectra were measured on a Shimadzu UV-260 spectrometer.

Materials. 3,6-Ditosyl-3,6-diazaoctanedioic acid (**5**) was prepared from 1,2-ethanediamine by the method in the literature.[10]

1,4,7,10,13,16-Hexaazacyclooctadecene (hexacyclen) (**13c**) was prepared from commercially available hexacyclen trisulfate (Aldrich Chem. Co.) by the method in the literature.[12]

Solvents were purified and dried by the standard procedures.

3,6-Ditosyl-3,6-diazaoctanedioyl Dichloride (6). 3,6-Ditosyl-3,6-diazaoctanedioic acid (**5**) (8.00 g, 16.5 mmol) was heated with thionyl chloride (100 ml) under reflux until the solution became clear. The excess thionyl chloride was evaporated at 60 °C. The remaining brownish crystals were repeatedly recrystallized from benzene to give **6** (7.30 g, 85% yield) as white crystals: mp 143—144 °C; IR (KBr) 2920, 2850, 1720, 1600, 1450, 1400, 1360, 1160, 1090, 1060, 960, 910, 805, 790, 750, 720 cm^{-1}; ^1H NMR ($CDCl_3$) δ=2.40 (6H, s), 3.26 (4H, s), 3.97 (4H, s), 7.50 (4H, d, J=7.5 Hz), and 7.59 (4H, d, J=7.5 Hz). Found: C, 46.26; H, 4.06; N, 5.31%. Calcd for $C_{20}H_{22}N_2O_6S_2Cl_2$: C, 46.07; H, 4.25; N, 5.37%.

3,6-Ditosyl-3,6-diazaoctanediamide (7). To a solution of **6** (72.2 g, 0.13 mol) in 700 ml of dichloromethane was introduced gaseous ammonia for 2 h at −78 °C to give white precipitates. After the excess ammonia was removed, the precipitates were collected by filtration, washed with water until the washing was no longer alkaline, and dried in vacuo. The precipitates were recrystallized from 2-methoxyethanol to give **7** as white crystals (48.6 g, 77%): mp 243.5—244.5 °C; IR (KBr) 3400, 3180, 2950, 2920, 1670, 1600,1500, 1460, 1420, 1360, 1310, 1290, 1250, 1190, 1160, 1120, 1090, 1050, 1020, 940, 900, 820, 790, 730 cm^{-1}; ^1H NMR (DMSO-d_6) δ=2.36 (6H, s), 3.26 (4H, s), 3.72 (4H, s), 6.97 (4H, brs), 7.42 (4H, d, J=7.5 Hz), and 7.51 (4H, d, J=7.5 Hz). Found: C, 49.99; H, 5.64; N, 11.33%. Calcd for $C_{20}H_{26}N_4O_6S_2$: C, 49.78; H, 5.43; N, 11.61%.

3,6-Ditosyl-3,6-diazaoctane-1,8-diamine (8). To a well-stirred suspension of 8.20 g (0.22 mol) of pulverized sodium borohydride in 300 ml of tetrahydrofuran (THF) containing 38.6 g (0.08 mmol) of **7** was added 55 ml (0.44 mol) of boron trifluoride etherate in 55 ml of dry THF in a period of 2 h at 0 °C under nitrogen atmosphere, then the mixture was refluxed for 12 h. After cooling at room temperature, the excess hydride was decomposed with water (60 ml), and 80 ml of 6 mol·dm^{-3} HCl solution was added. The solution was concentrated under reduced pressure. The residue was basified about pH 10 with 5 mol·dm^{-3} NaOH solution and extracted with dichloromethane (100 ml×3). Removal of the solvent gave solid mass. The crude product was recrystallized from methanol to afford white needles (23.2 g, 64%): mp 139—140 °C; IR (KBr) 3400, 2920, 2850, 1620, 1590, 1490, 1450, 1340, 1310, 1290, 1160, 1090, 1010, 960, 860, 810, 760, 720, 700 cm^{-1}; ^1H NMR (DMSO-d_6) δ=1.70 (4H, brs), 2.40 (6H, s), 2.65 (4H, t, J=7 Hz), 3.07 (4H, t, J=7 Hz), 3.22 (4H, s), 7.50 (4H, d, J=7.5 Hz), and 7.59 (4H, d, J=7.5 Hz). Found: C, 53.07; H, 6.68; N, 12.12%. Calcd for $C_{20}H_{30}N_4O_4S_2$: C, 52.84; H, 6.65; N, 12.32%.

4,7,13,16-Tetratosyl-1,4,7,10,13,16-hexaazacyclooctadecane-2,9-dione (9). A solution of **6** (7.30 g, 14 mmol) in dichlomethane (280 ml) and a solution of **8** (6.36 g, 14 mmol) and triethylamine (7.8 ml, 56 mmol) in dichloromethane (280 ml) were simultaneously added to a vigorously stirred dichloromethane (1700 ml) in a period of 12 h at the same dropping rate at 0 °C. Stirring was continued at 0 °C for additional 2 h. The solution was then washed with

water, dried with magnesium sulfate, and concentrated under reduced pressure to give the crude product. Purification by alumina column chromatography (the eluent: CH_2Cl_2) gave **9** as a white solid mass (6.33 g, 50%): IR (KBr) 3420, 2950, 2920, 1670, 1600, 1530, 1490, 1450, 1340, 1310, 1290, 1160, 1100, 1040, 1020, 1000, 930, 870, 820, 760, 720, 700 cm^{-1}; ^1H NMR ($CDCl_3$) δ=2.40 (12H, s), 3.31 (16H, brs), 3.72 (4H, s), 7.36 (8H, d, J=7.5 Hz), 7.45 (8H, d, J=7.5 Hz), and 8.11 (2H, brs). For the preparation of **10** the chromatographed **9** was used without further purification.

1,4,10,13-Tetratosyl-1,4,7,10,13,16-hexaazacyclooctadecane (10). To a well-stirred suspension of 1.14 g (30 mmol) of sodium borohydride in 120 ml of THF containing 4.15 g (5 mmol) of **9** was added 10 ml of boron trifluoride etherate (11.2 g, 80 mmol) in 40 ml of THF in a period of 1 h under nitrogen atmosphere at 0 °C, and the reaction mixture was refluxed for 24 h. After cooling at room temperature, the mixture was treated with water (25 ml) to decompose the excess hydride. The solution was concentrated under reduced pressure and extracted with dichloromethane (50 ml×5). The dichloromethane was evaporated, and 30 ml of 6 mol·dm^{-3} HCl solution was added to the residue. The acidic solution was heated at 80 °C for 1 h. After removal of excess HCl, saturated Na_2CO_3 solution was added until the evolution of gas ceased, and the product was extracted with dichloromethane (50 ml×3). The extracts were combined, dried, concentrated, and purified by alumina column chromatography (the eluent: CH_2Cl_2) to give **10** in 81%. The product was recrystallized from acetonitrile to give **10** (2.43 g, 56%): mp 208—212 °C; IR (KBr) 3420, 2940, 2860, 1590, 1500, 1450, 1340, 1310, 1290, 1190, 1160, 1120, 1090, 1040, 1010, 980, 920, 810, 760, 720 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.57 (2H, brs), 2.40 (12H, s), 2.73 (8H, t, J=5.0 Hz), 3.13 (8H, t, J=5 Hz), 3.31 (8H, s), 7.36 (8H, d, J=7.5 Hz), and 7.45 (8H, d, J=7.5 Hz). Found: C, 55.14; H, 6.31; N, 9.58%. Calcd for $C_{40}H_{54}N_6O_8S_4$: C, 54.90; H, 6.22; N, 9.60%.

1,10-Dibenzoyl-4,7,13,16-tetratosyl-1,4,7,10,13,16-hexaazacyclooctadecane (11a). To a stirred solution of **10** (0.60 g, 0.68 mmol) and triethylamine (0.40 ml, 2.8 mmol) in dichloromethane (30 ml) was added a solution of benzoyl chloride (0.38 ml, 2.8 mmol) in dichloromethane (5 ml) at 0 °C. After stirring for 8 h at room temperature, the reaction mixture was washed with water, dried, and concentrated under reduced pressure. The product was purified by silica-gel column chromatography (the eluent: CH_2Cl_2) to give **11a** (0.61 g, 83%): IR (KBr) 3070, 3040, 2940, 2870, 1720, 1640, 1600, 1500, 1450, 1420, 1350, 1310, 1160, 1120, 1100, 1040, 1020, 980, 910, 820, 740, 720, 700, 660 cm^{-1}; ^1H NMR ($CDCl_3$) δ=2.30 (12H, s), 3.0—3.9 (16H, m), 3.54 (8H, t, J=5 Hz), 7.37 (2H, dd, J=2 Hz, J'=9.5 Hz), 7.42 (4H, dd, J=7 Hz, J'=9.5 Hz), 7.43 (8H, d, J=7.5 Hz), 7.51 (8H, d, J=7.5 Hz), and 8.08 (4H, dd, J=2 Hz, J'=7 Hz).

1,10-Dioctanoyl-4,7,13,16-tetratosyl-1,4,7,10,13,16-hexaazacyclooctadecane (11b). The synthesis of **11b** was carried out in a similar manner to that of **11a**. Silica-gel chromatographic purification (the eluent: CH_2Cl_2) afforded **11b** in 94% yield: IR (KBr) 2930, 2850, 1720, 1640, 1600, 1460, 1420, 1350, 1310, 1160, 1090, 1040, 1020, 980, 910, 820, 740, 720, 700, 600 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.87 (6H, t, J=5 Hz), 1.27 (16H, brs), 1.63 (4H, t, J=5 Hz), 2.40 (12H, s), 3.08—3.81 (16H, m), 3.54 (8H, t, J=5 Hz), 7.43 (8H, d, J=7.5 Hz) and 7.51 (8H, d, J=7.5 Hz).

1,10-Dibenzyl-4,7,13,16-tetratosyl-1,4,7,10,13,16-hexaazacyclooctadecane (12a). To a solution of 0.70 g (0.64 mmol) of **11a** in 6 ml of THF was slowly added a solution of 11 ml of 1 mol·dm^{-3} diborane in THF (Aldrich Chem. Co.) at 0 °C under nitrogen atmosphere. The solution was then refluxed for 24 h. After cooling to room temperature, 10 ml of water was added to the solution, and the THF was evaporated. To the remaining residue was added 2 ml of 6 mol·dm^{-3} HCl solution, and the mixture was heated at 80 °C for 30 min. After concentration of the solution, the residue was basified with 10% LiOH solution (5 ml) and extracted with dichloromethane (30 ml×5). The extracts were concentrated under reduced pressure to give the crude product. Crystallization from benzene gave pure **12a** (0.49 g, 72%): mp 185—189 °C (decomp.); IR (KBr) 3060, 3030, 2930, 2860, 1630, 1600, 1500, 1460, 1400, 1340, 1310, 1160, 1100, 980, 920, 820, 740, 720, 700, 660 cm^{-1}; ^1H NMR ($CDCl_3$) δ=2.40 (12H, s), 2.65 (8H, t, J=7 Hz), 3.14 (8H, t, J=7 Hz), 3.24 (8H, s), 3.62 (4H, s), 7.35 (10H, s), 7.43 (8H, d, J=7.5 Hz), and 7.51 (8H, d, J=7.5 Hz). Found: C, 64.86; H, 6.41; N, 6.88%. Calcd for $C_{54}H_{66}N_6O_8S_4 \cdot 3/2C_6H_6$: C, 64.53; H, 6.45; N, 7.17%.

1,10-Dioctyl-4,7,13,16-tetratosyl-1,4,7,10,13,16-hexaazacyclooctadecane (12b). In a similar manner mentioned above, **12b** was synthesized. Recrystallization from acetonitrile gave pure **12b** in 81% yield: mp 160—163 °C (decomp); IR (KBr) 2930, 2850, 1630, 1600, 1500, 1460, 1350, 1310, 1160, 1100, 980, 820, 750, 710, 660 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.87 (6H, t, J=5 Hz), 1.25 (24 H, brs), 2.41 (12 H, s), 2.65 (12H, t, J=7 Hz), 3.14 (8H, t, J=7 Hz), 3.24 (8H, s), 7.43 (8H, d, J=7.5 Hz), and 7.51 (8H, d, J=7.5 Hz). Found: C, 61.32; H, 8.02; N, 7.94%. Calcd for $C_{56}H_{86}N_6O_8S_4$: C, 61.17; H, 7.88; N, 7.64%.

1,10-Dibenzyl-1,4,7,10,13,16-hexaazacyclooctadecane (13a). A solution of **12a** (106 mg, 0.1 mmol) in 0.7 ml of concd. H_2SO_4 was heated at 100 °C for 10 h. The solution was poured into an ice-cold water and basified with 10 mol·dm^{-3} NaOH solution, followed by extraction with dichloromethane (20 ml×5). The extracts were combined, dried, and concentrated under reduced pressure. The residue was chromatographed on an alumina column (the eluent: CH_2Cl_2) to give **13a** (30 mg, 69%): IR (neat) 3320, 3050, 2950, 2830, 1660, 1600, 1500, 1460, 1280, 1120, 1030, 910, 740, 700 cm^{-1}; ^1H NMR ($CDCl_3$) δ=2.50—2.95 (16H, m), 2.75 (8H, s), 3.62 (4H, s), 4.33 (4H, brs), and 7.25 (10H, s).

1,10-Dioctyl-1,4,7,10,13,16-hexaazacyclooctadecane (13b). In a similar manner, **13b** was prepared from **12b** in 60% yield: IR (neat) 3320, 2930, 2850, 1660, 1460, 1280, 1110, 910, 800, 740 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.88 (6H, t, J=5 Hz), 1.25 (24H, brs), 2.39—2.92 (16H, m), 2.82 (8H, s), and 3.98 (4H, brs).

Extraction Procedure. Extractability of unsubstituted and 1,10-disubstituted hexaaza-18-crowns for metal cations was examined in a similar manner to the method described in the literature.[13] A dichloromethane solution (5 ml) of hexaaza-18-crown (5×10^{-5} mol·dm^{-3}) and an aqueous solution (5 ml) containing equivalents of metal hydroxide (or metal chloride+sodium hydroxide) and picric acid were agitated at 25 °C for 1 h. An aliquot of the upper aqueous solution was withdraw, and UV spectrum was recorded. A similar extraction was performed without hexaaza-18-crown. The extractability was determined on the basis of the absorbance of picrate ion in the aqueous solutions by means

of the following equation:

$$\text{extractability } (\%) = [(A_0 - A)/A_0] \times 100$$

where A_0 is the absorbance in the absence of hexaaza-18-crown and A is the absorbance in the presence of hexaaza-18-crown.

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