Two distinct anion-binding modes and their relative stabilities†

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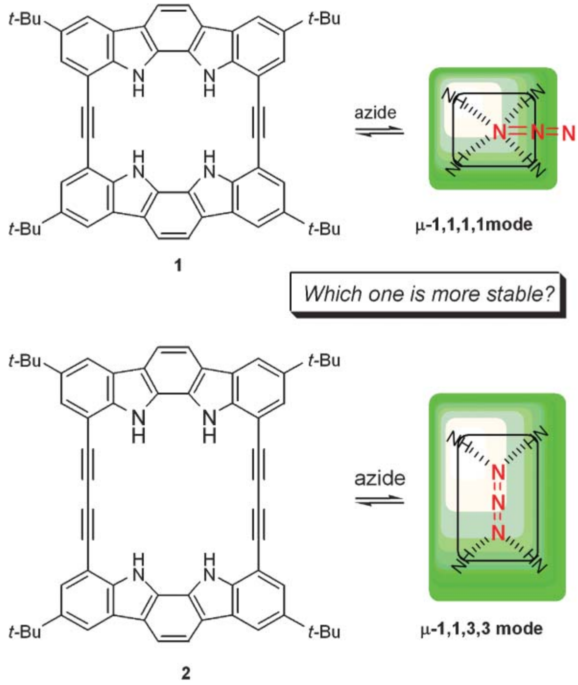
Two distinct hydrogen-bonding modes, end-on and end-to-end coordination, have been observed in the complexation between macrocycles and polyatomic anions such as azide and oxoanions.

The design and synthesis of anion receptors is a topic of current interest in supramolecular chemistry. A large variety of anion receptors capable of binding and sensing an anion through polar interactions in particular hydrogen bonds have been prepared for the last two decades.[1] It has been now realised that there exist some analogies between anion recognition chemistry and transition metal coordination chemistry in several aspects including the coordination number and geometry.[2] In anion recognition chemistry, the coordination number of an anion can be tuned by modifying the number of hydrogen bond donors in the receptor. However, it is much more difficult to predict the binding geometry because anion receptors in general possess some degree of flexibility, thus allowing for conformational change to optimize the binding affinity. This is also ascribed to the fact that the hydrogen bond is much weaker, less directional, and very sensitive to the environment relative to the transition metal–ligand bond.

Two macrocycles **1** and **2** studied here are extremely rigid, shape-persistent molecules without conformational flexibility. There is an internal planar cavity where four hydrogen bond donors of indole NHs[3] are conversed to bind anions by hydrogen bonding interactions as previously proven with **1**.[3b] Herein, we have described two macrocycles which possess the anion-binding cavity of different size, thus leading to completely different hydrogen-bonding modes (Scheme 1). Upon complexation of **1** and **2** with azide, two unique hydrogen–bonding modes of μ_4–1,1,1,1 (end-on) and μ_4–1,1,3,3 (end-to-end) have been found in the solid state. The latter binding mode was determined to be energetically much more stable than the former one in solution.

The synthesis and characterization of macrocycles **1** and **2** are described in the Supporting Information.† The computer modeling studies[4] show that **1** has a very small, square cavity with distances of 2.6 Å (side) and 3.7 Å (diagonal) between indole NHs, thus allowing for the coordination of one small atom such as oxygen and nitrogen. On the other hand, **2** contains a more spacious, rectangular cavity with NH distances of 2.6 Å (side), 5.1 Å (side), and 5.8 Å (diagonal) to which more than one atom of polyatomic anions can be simultaneously coordinated by hydrogen bonds. These putative binding modes have been unambiguously verified by single crystal X-ray diffraction analyses of two different complexes of tetrabutylammonium azide with macrocycles **1** and **2**.



Scheme 1 Macrocycles **1** and **2** and their plausible binding modes.

The crystal structures of the **1**·N_3^- complex‡ are shown in Fig. 1.[5] As anticipated based on the cavity size, only one terminal nitrogen of azide is coordinated to the cavity by four hydrogen

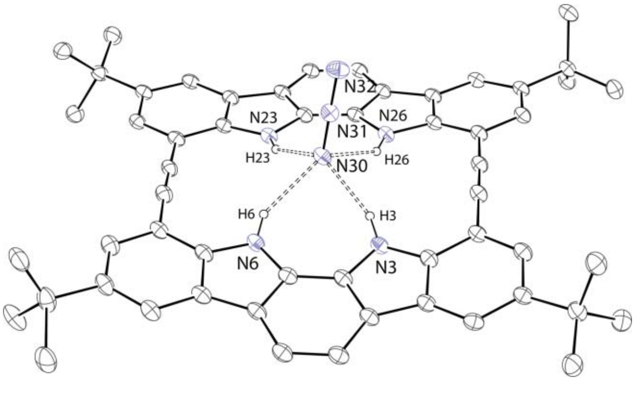


Fig. 1 ORTEP view of the X-ray crystal structure of **1**·N_3^- complex. Tetrabutylammonium and hydrogen atoms except indole NHs are omitted for clearance, and hydrogen bonds are indicated as dashed lines.

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bonds adopting a μ$_4$–1,1,1,1 (end-on) coordination mode. The average distance and angle of NH (indole)···N (azide) hydrogen bonds are 2.13 Å and 150°, respectively.[6] The countercation tetrabutylammonium is located on the aryl plane and close to the other end nitrogen of azide, stabilized by both cation–π and electrostatic interactions (see Supporting Information†), which may prevent the formation of a possible 2 : 1 (**1**–azide) sandwich-type complex. It should be noted that the bond distances between nitrogen atoms of azide become unequal in the complex. The average N–N bond distance (1.191 Å) of hydrogen-bonded side is longer than that (1.171 Å) of the other side,[6] which can be rationalized by resonance structures of azide.

$$\left[:\ddot{\mathrm{N}}=\mathrm{N}=\ddot{\mathrm{N}}:\right]^{-} \leftrightarrow \left[:\underset{\cdot\cdot}{\ddot{\mathrm{N}}}-\mathrm{N}\equiv\mathrm{N}:\right]^{-} \tag{1}$$

The crystal structure of the **2**·N_3^- complex‡ is drastically different from that of the **1**·N_3^- complex (Fig. 2). First, the azide ion is nicely fitted in the cavity of macrocycle **2** in a μ$_4$–1,1,3,3 (end-to-end) coordination mode, which results in each terminal nitrogen making two hydrogen bonds (H···N distances 2.11 and 2.05 Å) with indole NHs. Second, the azide N–N bond distance (1.187 Å) in **2**·N_3^- complex bearing the crystallographic inversion center is slightly shorter than that of the hydrogen-bonded side but longer than that of the other side in **1**·N_3^- complex. Again, tetrabutylammonium is placed on the aromatic plane adjacent to the bound azide as the result of cation–π and electrostatic interactions.

It would be very interesting to compare the stabilities of two complexes which have the same number of hydrogen bonds but different coordination modes. The hydrogen bonding formation in solution was confirmed by ^{1}H NMR spectroscopy, showing large down field shifts ($\Delta\delta > 2$ ppm) of the NH signals of macrocycles **1** and **2** when complexed with azide (see Supporting Information†). For quantitative comparison, the association constants (K_a, M^{-1}) were determined by UV-vis spectroscopy in a polar medium 10% (v/v) methanol–acetone at 23 ± 1 °C.[7] Nonlinear squares fitting analyses[8] of the titration curves provide the association constants of 2300 M^{-1} for **1** and 81000 M^{-1} for **2**, indicating that the hydrogen bonding mode of μ$_4$–1,1,3,3–azide is more stable than the corresponding μ$_4$–1,1,1,1-azide mode by the free energy difference ($\Delta\Delta G$) of −8.8 kJ mol^{-1}.

Next, the binding properties of macrocycles **1** and **2** with other anions were investigated and the results are summarized in Table 1.

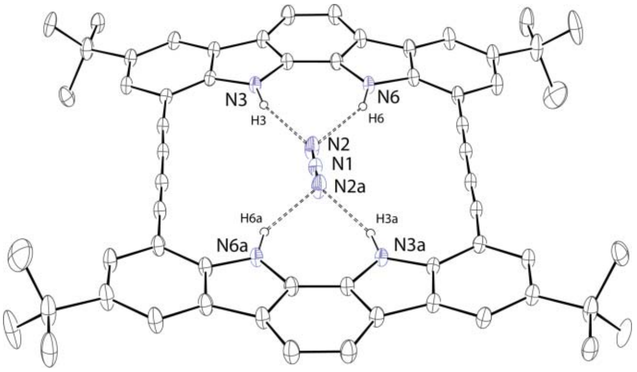

Fig. 2 ORTEP view of the X-ray crystal structure of **2**·N_3^- complex. Tertabutylammonium and hydrogen atoms except indole NHs are omitted for clearance, and hydrogen bonds are indicated as dashed lines.

Table 1 Association constants (K_a ± 20%, M^{-1}) of macrocycles **1** and **2** with anions in 10% (v/v) methanol–acetone at 23 ± 1 °C

Anion[a]	Association constant (K_a, M^{-1})[b] **1**	**2**	Ratio of K_a (**2/1**)
Cl^-	1800	430	0.24
Br^-	72	320	4.4
I^-	<10	2400	>240
N_3^-	2300	81 000	35
CH_3COO^-	21 000	170 000	8.1
$H_2PO_4^-$	4300	220 000	51
NO_3^-	94	15 000	160
HSO_4^-	81	13 000	160

[a] Anions as tetrabutylammonium salts were used. [b] Titrations were all duplicated in UV/visible spectroscopy and errors in association constants were less than 20%.

Two trends are apparent. First, the association constants of **1** with halides are increasing in the order of $Cl^- > Br^- > I^-$, being parallel with the order of hydrogen bond acceptability of halides. On the other hand, macrocycle **2** with the larger cavity shows the highest binding affinity to iodide among halides, reflecting the size complementarity between the binding cavity and anions. The formation of 1 : 1 complexes was confirmed by continuous variation method (Job's plot).[9] These results suggest that the cavity of **2** is suitably matched with iodide to form four hydrogen bonds but slightly spacious for smaller halides, chloride and bromide. Second, the association constants of macrocycle **1** in general increase as the basicities of anions increase regardless of whether the anion is monoatomic or polyatomic. However, macrocycle **2** shows much stronger binding affinities to polyatomic oxoanions relative to monoatomic halides. For example, hydrogen sulfate and nitrate bind to **2** much more strongly than chloride does, while the latter binds to **1** with the higher affinity. These results must be associated with different binding modes of two macrocycles with anions (Scheme 1); the oxoanions may bind to **1** by single atom coordination of a μ$_4$–1,1,1,1 (end-on) mode due to the limited space of the cavity as mentioned earlier, but they can be coordinated to **2** in a bridged way of a μ$_4$–1,1,3,3 (end-to-end) hydrogen-bonding mode. As seen in Table 1, the latter mode was proven more stable than the corresponding former despite two binding modes possessing the identical number and kind of hydrogen bonds.

In conclusion, two unique hydrogen–bonding modes have been observed for the first time between rigid shape–persistent macrocycles and polyatomic anions such as azide and oxoanions. The binding mode of a polyatomic anion depends on the cavity size of the macrocycle; macrocycle **1** with a smaller cavity adopts a μ$_4$–1,1,1,1 (end-on) hydrogen bond mode, while macrocycle **2** with a larger one display a more stable μ$_4$–1,1,3,3 (end-to-end) mode.

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Notes and references

‡ Single crystals of [(tetrabutylammonium)$_3$(**1**·N_3)$_3$]3.5(diethylether) were obtained as by layering diethyl ether into a toluene–CH_3CN solution

containing a 1 : 1 molar ratio of **1** and $Bu_4N^+N_3^-$. The crystals were coated with paratone oil to prevent the loss of crystallinity upon exposure to air. The diffraction data were measured with synchrotron radiation (λ = 0.70000 Å) using a 4AMXW ADSC Quantum-210 detector with a platinum-coated silicon double-crystal monochromator at the Pohang Accelerator Laboratory, Korea. ADSC Quantum-210 ADX Program was used for data collection and the HKL2000 (*Ver*. 0.98.689) was used for cell refinement, reduction, and absorption correction. All structures were solved by direct methods and refined by full-matrix least-squares calculations with the SHELXTL-PLUS software package. Crystal data for [(tetrabutylammonium)$_3$(**1**·N$_3$)$_3$]·3.5(diethyl ether): $C_{230}H_{299}N_{24}O_{3.5}$, fw = 3455.93, triclinic, space group $P\bar{1}$, T = 90(2) K, a = 22.506(5) Å, b = 22.564(5) Å, c = 22.614(5) Å, α = 65.145(5)°, β = 85.503(5)°, γ = 80.707(5)°, V = 10283(4) Å^3, Z = 2, ρ_{calc} = 1.116 g cm^{-3}, μ(synchrotron, λ = 0.70000 Å) = 0.066 mm^{-1}. Refinement converged to final $R1$ = 0.0704 ($I > 2\sigma(I)$), w$R2$ = 0.2274 for all data, GOF = 1.072, max./min. residual electron density 1.254/−0.638 e Å^3.

Single crystals of [(tetrabutylammonium)(**2**·N$_3$)](hexane) were obtained as by layering hexane into a CH_2Cl_2/EtOAc/CH_3CN solution containing a 1:1 molar ratio of **2** and $Bu_4N^+N_3^-$. Crystal data for [(tetrabutylammonium)(**2**·N$_3$)](hexane): $C_{82}H_{102}N_8$, fw = 1199.72, monoclinic, space group $P2_1/c$, T = 93(2) K, a = 18.459(4) Å, b = 17.029(3) Å, c = 12.014(2) Å, β = 103.43(3)°, V = 3673.2(13) Å^3, Z = 2, ρ_{calc} = 1.085 g cm^{-3}, μ(synchrotron, λ = 0.70000 Å) = 0.063 mm^{-1}. Refinement converged to final $R1$ = 0.0946 ($I > 2\sigma(I)$), w$R2$ = 0.2885 for all data, GOF = 1.070, max./min. residual electron density 0.905/−0.400 e Å^3. CCDC 643421–643422. For crystallographic data in CIF or other electronic format see DOI: 10.1039/b707032b

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6 There are three independent azide complexes in the unit cell, all of which are virtually identical structures with only minor deviation in the bond distance and angle (see Supporting Information†). Therefore, the distances and angles reported here are the averages of three complexes.

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