Cucurbit[7]uril host-guest and pseudorotaxane complexes with α,ω-bis(pyridinium)alkane dications†

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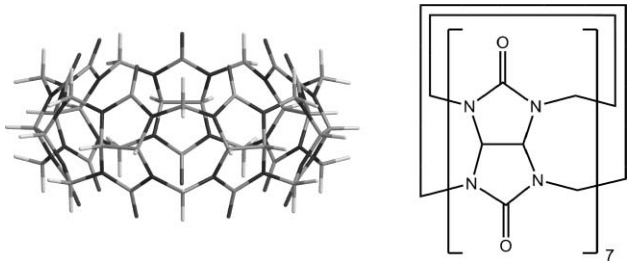
The host molecule cucurbit[7]uril forms very stable host-guest complexes (1:1 and 2:1) and [2]pseudorotaxanes with α,ω-bis(pyridinium)alkane dications in aqueous solution. With the dications containing pyridinium, 2- and 3-picolinium, and 4-dimethylaminopyridinium end groups and a hexyl chain, [2]pseudorotaxanes are formed with one equivalent of CB[7] positioned over the central chain. A second equivalent of CB[7] encapsulating one of the end groups results in the translocation of the first CB[7] to the other end group. For the dications with these end groups, the 2:1 host-guest complexes exhibit stability constants which are considerably smaller than the 1:1 values as the result of steric and electronic repulsions between the two CB[7] hosts.

Introduction

The cucurbit[*n*]uril (CB[*n*], where $n = 5$–8 and 10) family of macrocyclic host molecules, comprised of *n* glycoluril units bridged by 2*n* methylene groups, have been demonstrated to form exceedingly stable host-guest complexes with cationic organic and organometallic guests in aqueous solution, as a result of a hydrophobic cavity accessed through two restrictive polar carbonyl-lined portals.[1] The CB[7] host (Scheme 1),[2] in particular, has the appropriate cavity size to include guests such as aromatic rings,[3,4] metallocenes,[5] and platinum(II) antitumor agents.[6] Cucurbiturils have been applied to the recognition of amino acids, peptides,[7] and drugs,[8] including vitamin B_{12}.[8b] The encapsulation of guests can significantly affect chemical properties, such as the pK_a of nitrogen- and carbon-centered acids and their absorption and fluorescence spectra.[9] While the majority of cationic guests are included with the more hydrophobic portion of the guest within the cavity of CB[7] and the cationic charge(s) outside the cavity adjacent to the carbonyl oxygens on the portal(s), we have demonstrated that more hydrophobic and charge-diffuse cations, such as tetraalkylammonium and tetraalkylphosphonium guests, may reside partially or entirely within the cavity.[10]



Scheme 1 Cucurbit[7]uril.

Cucurbiturils have also been employed in the preparation of a significant number of mechanically-interlocked supramolecular complexes,[11] including [n]rotaxanes, [n]semirotaxanes, [n]pseudorotaxanes, and [n]catenanes with CB[5],[12] CB[6],[11a,13] CB[7],[14,15] and CB[8][16] acting as the cyclic component. With the polar carbonyl groups lining the rims of the cucurbiturils, the end groups on the threads can prevent dissociation of the rotaxanes into their cyclic bead and linear thread components through steric and/or electrostatic means. With the polypseudorotaxanes and polyrotaxanes, molecular switches and shuttles have been demonstrated[11] using proton transfer,[11b,c,13b,c,d] electron transfer,[11c] light,[14i,n] and heat[13d] as external stimuli. In many instances polymers are used as threads in the cucurbituril polypseudorotaxane and polyrotaxanes. The encapsulation of polyaniline by CB[6] or CB[7], for example, leads to the stabilization of the conductive radical cationic form.[12i,13b,c] We have shown that the tetracationic guest $[CH_3bpy(CH_2)_6bpyCH_3]^{4+}$ (bpy^{2+} = 4,4′-bipyridinium) forms a [2]pseudorotaxane with the addition of one equivalent of CB[7], with the host residing over the central hexyl chain.[14f] The addition of a second equivalent of the host and its encapsulation of one of the viologen end groups results in the movement of the first CB[7] to the other end group. Liu *et al.*[14g] and Schmitzer and coworkers[14d] have each demonstrated that addition of cyclodextrins to 1:1 complexes between CB[7] and a cationic guest with multiple binding sites can result in the movement of the CB[7] host between binding positions.

In the present study, a series of dicationic organic guests (Scheme 2) containing unsubstituted and substituted (2- and 3-methyl, 4-dimethylamino, and 4-*tert*-butyl) pyridinium end groups and aliphatic linkers (ethyl, hexyl and *p*-xylyl) have been encapsulated by one or two CB[7] host molecules in aqueous solution, to form 1:1 and 2:1 host-guest complexes in the forms of [2]- and [3]-pseudorotaxanes, respectively. The stoichiometries and nature of the inclusions, and the stability constants and their dependencies on the nature of the end groups and linkers, have

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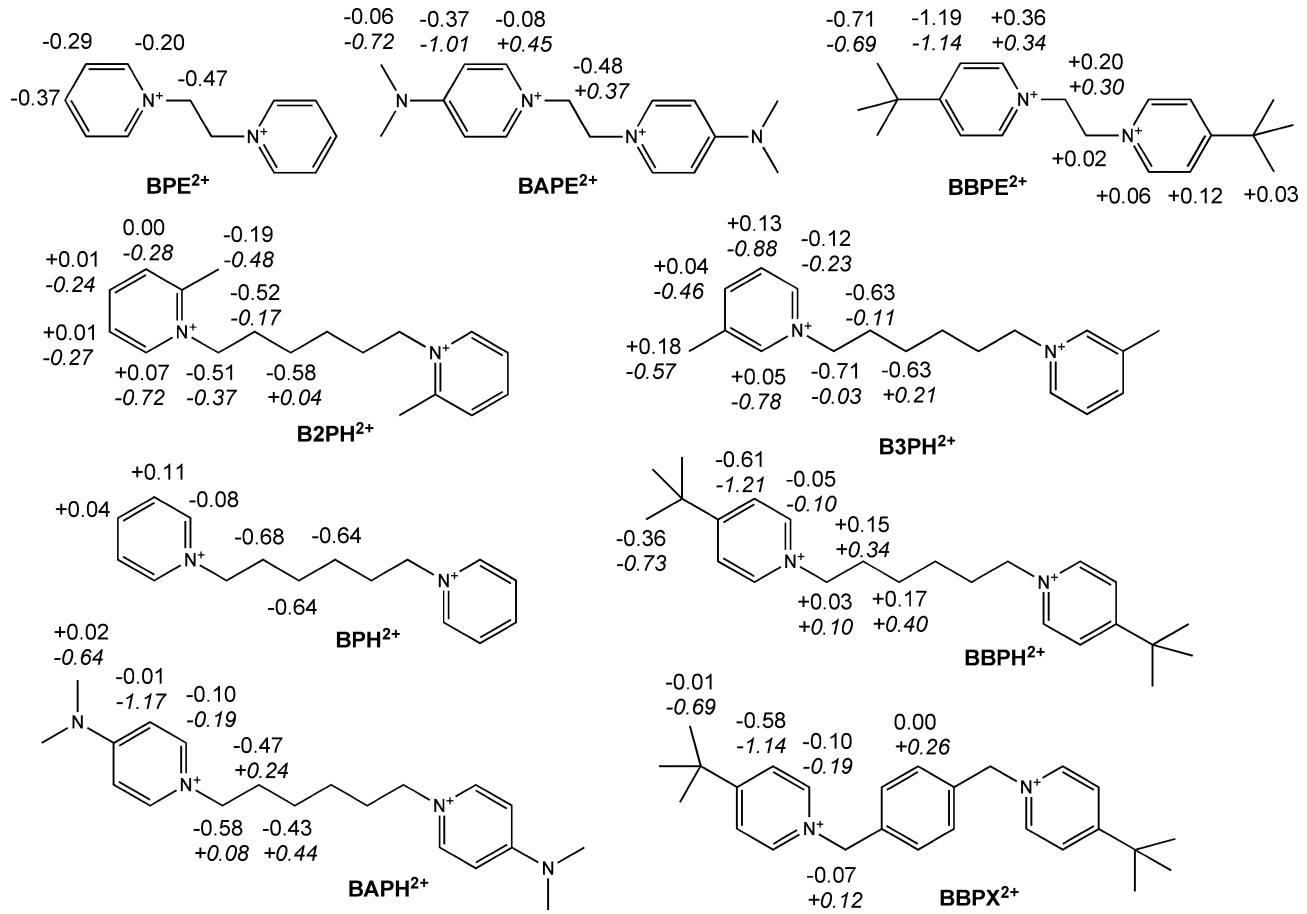

Scheme 2 Structures of the guests and complexation induced chemical shifts ($\Delta\delta_{lim}$ in ppm) for the 1:1 and 2:1 (italics) host-guest complexes with cucurbit[7]uril.

been investigated using ^{1}H NMR and UV spectroscopy and ESI mass spectrometry.

Results and discussion

The formations of host-guest and pseudorotaxane complexes of CB[7] with the dicationic guests in this study were confirmed by the use of ^{1}H NMR and UV spectroscopy and ESI mass spectrometry.[17] ^{1}H NMR spectroscopy is particularly useful for determining the position(s) of the guest which is encapsulated by the CB[7] host(s), as the complexation-induced chemical shifts ($\Delta\delta_{lim} = \delta_{bound} - \delta_{free}$) in the guest proton resonances are indicative of their location within the cavity ($\Delta\delta_{lim} < 0$ ppm) or outside the cavity near the carbonyl-lined portal ($\Delta\delta_{lim} > 0$ ppm). The titrations of the guests in this study with CB[7] reveal a range of guest exchange rates, with respect to the ^{1}H NMR timescale, from slow (separate resonances for the free and bound guests) to fast (observed resonances represent an average of free and bound guest resonances), with intermediate (considerable broadening of the averaged resonances) exchange observed with the $BBPX^{2+}$ guest.

The 1,2-bis(1-pyridinium)ethane dication (BPE^{2+}) forms only a 1:1 complex with upfield shifts in the pyridinium and ethane protons, suggesting that the CB[7] is moving over both the pyridinium and ethane regions rapidly on the ^{1}H NMR timescale. There is no additional change in the chemical shifts of the guest protons upon additions of more than one equivalent of CB[7] and the ESI mass spectrum displays no peaks associated with a 2:1 host-guest complex. All of the guests, with the exception of BPE^{2+}, exhibit binding by a second CB[7] host at host-guest ratios greater than 1:1, which can be demonstrated using ^{1}H NMR and UV spectroscopy and ESI mass spectrometry.

With the 1,2-bis(4-dimethyaminopyridinium)ethane dication guest ($BAPE^{2+}$) there are two possible resonance structures as indicated in Fig. 1. The first has the positive charges localized on the pyridinium nitrogens, with the other bearing the positive charges on the amine nitrogens, rendering the pyridinium groups neutral. Substantial double-bond character in the exocyclic carbon-nitrogen bond has been established in 1-methyl-4-alkylaminopyridinium cations at room temperature in aqueous solution by means of ^{13}C NMR measurements.[18] In the latter resonance structure, the encapsulation of the guest by CB[7] would place the positive charges adjacent to the polar carbonyl groups on the portals of the host and stabilize the resonance structure. The contribution of this resonance structure may be seen in the ^{1}H NMR spectrum upon addition of one equivalent of the host (Scheme 2 and Fig. 2).

The changes in the chemical shifts of the guest protons upon inclusion by one CB[7] host would be a combination of complexation-induced chemical shift changes and chemical shifts arising from a change in the relative contributions of the

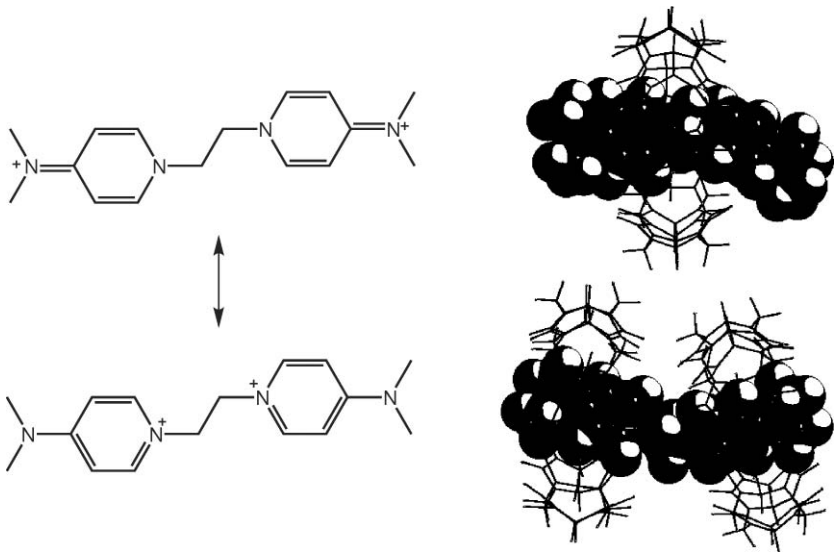

Fig. 1 The quinoidal (top left) and pyridinium (bottom left) resonance structures of the $BAPE^{2+}$ dication and an energy-minimized structures of the $\{BAPE{\cdot}CB[7]\}^{2+}$ (top right) and $\{BAPE{\cdot}2CB[7]\}^{2+}$ (bottom right) complexes.

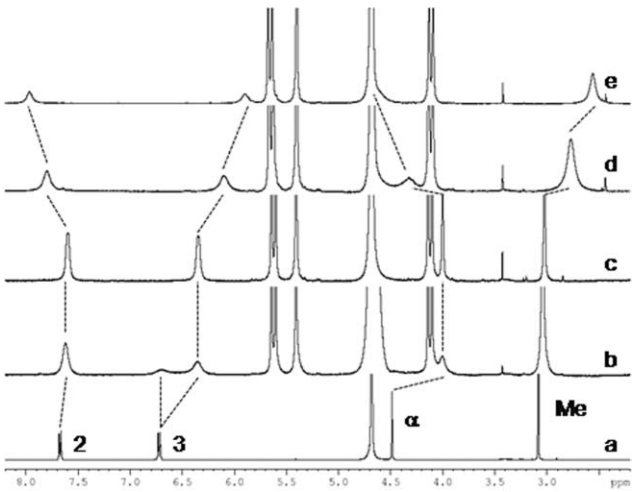

Fig. 2 ^1H NMR spectra of $BAPE^{2+}$ in the (a) absence and presence of (b) 0.73, (c) 1.14, (d) 1.86, and (e) 2.34 equivalents of CB[7] in D_2O.

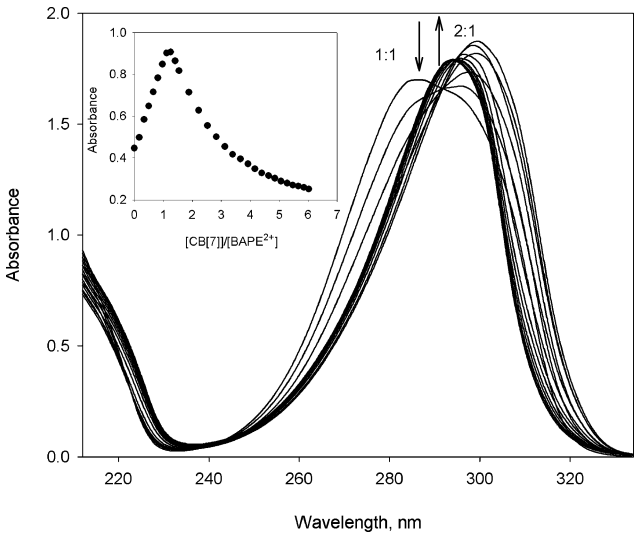

Fig. 3 UV titration of $BAPE^{2+}$ (5.1×10^{-5} mol dm^{-3}) with CB[7]. Inset: plot of absorbance at 314 nm as a function of $[CB[7]]/[BAPE^{2+}]$.

two resonances structures of the guest. The shift in the relative contributions of the resonance structures from the pyridinium structure to the quinoidal structure would be expected to result in upfield shift shifts in all of the proton resonances. The slight upfield shift in the methyl resonances is thus a result of the upfield shift for the quinoidal resonance structure combined with an expected downfield shift in the peak when it is placed outside of the portals of the CB[7] host in the 1:1 complex. The ^1H NMR spectra indicate that the formation/dissociation of the 1:1 host-guest complex with $BAPE^{2+}$ is slow on the NMR time scale (observance of peaks for both the free and bound guest), while the 2:1 complex exhibits exchange which is fast on the NMR timescale (peaks represent average of 1:1 and 2:1 resonances). This would be consistent with the location of the CB[7] hosts on the pyridinium rings in the 2:1 complex.

The UV spectrum of the $BAPE^{2+}$ guest exhibits noticeable changes upon the addition of increasing amounts of CB[7], as shown in Fig. 3. With up to one equivalent of the host, the λ_{max} value increases from 286 nm to 298 nm for the 1:1 complex, with an isosbestic point at 292 nm. With more than one equivalent, the peak moves to 294 nm, with an isosbestic point at 296 nm. The second, weaker binding results in the formation of the 2:1 host-guest complex. The initial bathochromic shift is likely a result of the stabilization of the quinoidal resonance structure by the first CB[7], which is somewhat diminished when a second CB[7] is attached, resulting in a slight hypsochromic shift as the resonance equilibrium is shifted back towards the pyridinium form. Loeb and coworkers have observed the opposite behaviour in the interaction of the diprotonated 1,2-bis(4-(N,N′-dimethylamino)bipyridinium)ethane tetracation with dibenzo-24-crown-6, in which the crown host only forms a complex with the protonated pyridinium resonance structure and not the deprotonated pseudo-quinoidal structure.[19] In this host-guest complex,

it is the central $^{+}NCH_2CH_2N^{+}$ moiety which forms ion-dipole interactions with the crown ether, while in the present system, the pseudo-quinoidal resonance structure provides the right match between the positive charges on the guest and the polar carbonyl groups on the portals in the 1:1 CB[7] host-guest complex.

With the hydrophobic 4-*tert*-butyl groups on the pyridinium rings, CB[7] forms a very stable 1:1 complex with $BBPE^{2+}$, with the host residing over one of the *tert*-butylpyridinium end groups, but causing small complexation-induced chemical shifts in the non-complexed end group. The slow exchange of the ligand on the ^1H NMR timescale is evident in the spectra in Fig. 4, with separate aromatic resonances for the free guest, the non-complexed and complexed rings of the 1:1 complex, and the fully complexed 2:1 host-guest complex. The addition of the second CB[7] has little effect on the chemical shifts of the protons on the pyridinium ring which was first complexed.

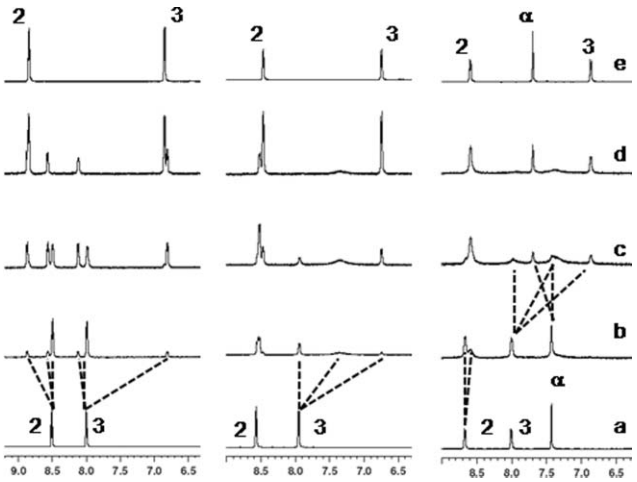

Fig. 4 Downfield portions of the ^1H NMR spectra of $BBPE^{2+}$ (left, (a) 0.00, (b) 0.30, (c) 0.73, (d) 1.57, and (e) 2.19 equiv of CB[7]), $BBPH^{2+}$ (middle, (a) 0.00, (b) 0.34, (c) 0.90, (d) 1.57, and (e) 2.48 equiv of CB[7]), and $BBPX^{2+}$ (right, (a) 0.00, (b) 0.56, (c) 1.13, (d) 1.36, and (e) 2.53 equiv of CB[7]) in the presence of CB[7] in D_2O.

When the aliphatic linker is lengthened from ethyl to hexyl, the addition of one equivalent of CB[7] may result in the formation of a 1:1 host-guest complex in the form of a [2]pseudorotaxane. A crystal structure of the 1:1 host-guest complex between CB[6] and the 1,6-bis(1-pyridinium)hexane dication (BPH^{2+}) reveals that the host is positioned over the hexyl linker, with the cationic pyridinium end groups located near the polar portals.[13h] The BPH^{2+} dication exhibits strong 1:1 complex formation with CB[7], followed by a much weaker 2:1 complex formation as excess CB[7] is added.[17] This is manifested in significant upfield shifts in the hexyl chain protons, with small downfield shifts in the *meta* and *para* protons of the pyridinium rings. With the weak complexation of the guest by a second CB[7], the trend in the chemical shift changes, with upfield shifts in the pyridinium protons and downfield shifts in the hexyl protons. While it is not possible to extract accurate limiting chemical shifts for the 2:1 complex, the directions of the chemical shift changes support the inclusion of one or both pyridinium end groups.

With both of the $B2PH^{2+}$ and $B3PH^{2+}$ guests, the ^1H NMR spectra also indicate that the first CB[7] resides over the hexyl chain, resulting in the formations of [2]pseudorotaxanes. Upon the addition of the second equivalent of CB[7], the original CB[7] is translocated from the hexyl chain to being positioned over the picolinium end group while the second CB[7] encapsulates the other end group in a stable 2:1 host-guest complex. A similar process is observed with $BAPH^{2+}$, while for $BBPH^{2+}$ $BBPX^{2+}$ there are no formations of a [2]pseudorotaxane species, but rather 1:1 and 2:1 host-guest complexes, with sequential binding of the 4-*tert*-butylpyridinium end groups occurring. This is indicated by a doubling of the $\Delta\delta_{lim}$ values for the methyl and aromatic proton resonances on going from the 1:1 species (average of complexed and non-complexed end groups) to the 2:1 host-guest species (see the H3 proton in Fig. 4).

Table 1 The 1:1 and 2:1 host-guest stability constants for the CB[7] complexes in D_2O (pH = 4.75 (0.050 mol dm^{-3} NaOAC/HOAc) at 25 °C

Guest	$K_{1:1}$, dm^3 mol^{-1}	$K_{2:1}$, dm^3 mol^{-1}	$K_{1:1}/K_{2:1}$
BPE^{2+}	$(3.1 \pm 0.6) \times 10^6$ [a]		
$BAPE^{2+}$	$(7.4 \pm 1.3) \times 10^7$ [a]	$(1.6 \pm 0.7) \times 10^5$ [b,c]	460
$BBPE^{2+}$	$(1.0 \pm 0.2) \times 10^{11}$ [d,e]	$(8.1 \pm 2.3) \times 10^9$ [d,e]	12
BPH^{2+}	$(4.8 \pm 1.1) \times 10^8$ [d]	$(8 \pm 2) \times 10^1$	6×10^6
$B2PH^{2+}$	$(2.4 \pm 0.4) \times 10^7$ [a]	$(3.2 \pm 1.5) \times 10^4$ [b]	750
$B3PH^{2+}$	$(1.6 \pm 0.3) \times 10^8$ [a]	$(2.3 \pm 1.2) \times 10^4$ [b]	7000
$BAPH^{2+}$	$(1.5 \pm 0.5) \times 10^8$ [a,f]	$(6.8 \pm 2.6) \times 10^5$ [a,b,c]	220
$BBPH^{2+}$	$(5.2 \pm 1.2) \times 10^{10}$ [d,e]	$(2.1 \pm 0.4) \times 10^9$ [d]	25
$BBPX^{2+}$	$(1.2 \pm 0.3) \times 10^{10}$ [f]	$(7.9 \pm 1.9) \times 10^8$ [d]	15

[a] Using 3-(trimethylsilyl)propionic acid as competitor.[2b] [b] Using $N(CH_3)_4^+$ as competitor.[10] [c] Using $N(CH_2CH_3)_4^+$ as competitor.[10] [d] Using *p*-xylenediamine as competitor.[2b] [e] Using $FeCp(CpCH_2N(CH_3)_3)^+$ as competitor.[2b] [f] Using $BzN(CH_3)_3^+$ as competitor.[10]

The 1:1 and 2:1 (with the exceptions of BPE^{2+} and BPH^{2+}) CB[7] host-guest stability constants with the guests in this study were too large to be determined by conventional ^1H NMR or UV-visible spectroscopic titrations. Instead, ^1H NMR competition experiments, using a variety of competitor guests, were carried out at 25 °C and pH 4.75 (0.05 mol dm^{-3} NaOAc/HOAc buffer) with a deficiency of CB[7]. In the case of BPH^{2+}, a Benesi-Hildebrand double reciprocal plot of $1/\Delta\delta$ against 1/[CB[7]] afforded the stability constant from the intercept/slope ratio.[17] The magnitudes of the 1:1 and 2:1 host-guest stability constants (Table 1) for the guests in this study depend on the natures of the substituents on the pyridinium end groups and the nature and length of the aliphatic linkers.

The largest 1:1 stability constant of 1.1×10^{11} dm^3 mol^{-1} is observed for $BBPE^{2+}$, likely the result of the hydrophobic nature of the *tert*-butyl substituent and the possibility of the second positive charge interacting in an ion-dipole fashion with the polar portal of CB[7]. The flexibility in the ethane bridge would allow for the pyridinium ring to approach the portal, accounting for the small downfield shifts in the non-complexed end of the guest molecule. The other guests bearing the *tert*-butyl substituents, $BBPH^{2+}$ and $BBPX^{2+}$, have only slightly smaller 1:1 stability constants.

The [2]pseudorotaxanes formed by the 1:1 complexation of the central chains by CB[7] in the cases of the BHP^{2+}, $B2PH^{2+}$, $B3PH^{2+}$, and $BAPH^{2+}$ have stability constants in the range of 2×10^7 to 5×10^8 dm^3 mol^{-1} (Table 1). We have determined a somewhat higher value of $(3.9 \pm 0.9) \times 10^9$ dm^3 mol^{-1} for the 1:1 CB[7] complex of the 1,6-diammoniumhexane dication, which exhibits no formation of a 2:1 complex.[20] Kaifer and coworkers have reported a lower limit

for the binding of the α,α-bis(1-pyridinium)-*p*-xylene dication to CB[7] of 1.0×10^6 dm^3 mol^{-1} in D_2O containing 0.20 mol dm^{-3} NaCl.[15] Without the 4-*tert*-butyl substituents found in $BBPX^{2+}$, the CB[7] complexes the internal *p*-xylene linker, rather than the pyridinium head groups. Even with 4-pyridylpyridinium groups attached to the *p*-xylene core, Kaifer observed binding to the center of the guest forming a [2]pseudorotaxane, allowing for capping of the thread with bulky stoppers to form a [2]rotaxane.

The 2:1 stability constants were also determined by ^{1}H NMR competition experiments in solutions with CB[7]:guest concentration ratios of approximately 1.5:1, assuming strong binding of the 1:1 host-guest complex. If a statistical binding phenomenon is operating, with no inhibitory effect of the first host molecule on the strength of the binding of the second host molecule, then the ratio of the 1:1 stability constant to the 2:1 stability constant ($K_{1:1}/K_{2:1}$) would be 4.[21] This would assume that the first and second host molecules occupy similar binding sites. With all of the guests in this study, the decrease in the strength of the second binding exceeds a factor of 4 indicating the first host molecule has a detrimental effect on the binding of the second host (Table 1).

In the cases where 1:1 and 2:1 binding is limited to the end groups of the guest, such as with $BBPE^{2+}$, $BBPH^{2+}$, and $BBPX^{2+}$, the ratios are in the range of 12–25, indicating a minor deviation from statistical binding. Kaifer and coworkers have observed that the $K_{1:1}/K_{2:1}$ ratios for CB[7] binding to $HO_2C(CH_2)_n bpy(CH_2)_n CO_2H^{2+}$ guests (n = 6, 7, and 10) are in the range of 25–45, also evidence of a degree of negative cooperativity.[11c,14] Sun and coworkers have recently shown that with tetracationic threads composed of methyl viologen and N,N-dimethyl-3,3′-dimethyl-4,4′-bipyridinium end groups and either propyl or hexyl linkers, the CB[8] host will form 1:1 and 2:1 host-guest complexes with the host residing exclusively over the bipyridinium end groups.[22] A weaker (and more dynamic) 2:1 complex is observed for the shorter propyl linker compared with the hexyl linker, based on ^{1}H NMR spectra.

In situations where there is movement of the first CB[7] host molecule from the center of the guest to an end group, upon binding of the second CB[7] over the other end group, the difference between $K_{1:1}$ and $K_{2:1}$ will depend on the natures of the center and end groups and the distance between the two end groups. We have previously reported that for the tetracationic guest $[CH_3bpy(CH_2)_6bpyCH_3]^{4+}$, the $K_{1:1}/K_{2:1}$ ratio for CB[7] binding is approximately 9. This relatively small decrease can be attributed to the fact that both the central unit and the viologen end groups provide two positive centers for the hosts. In the present study, the movement of first CB[7] from the hexyl chains in BPH^{2+}, $B2PH^{2+}$, $B3PH^{2+}$, and $BAPH^{2+}$ to the end groups results in reductions in $K_{2:1}$, relative to $K_{1:1}$, in the range of 2×10^2 to 6×10^6 fold, with the diminution factor being inversely related to the strength of the binding to the end groups. While the guest in the 1:1 host-guest species provides a positive charge located near each portal of the CB[7] in the [2]pseudorotaxanes, there is only one positive charge forming an ion-dipole interaction with each CB[7] in the 2:1 complexes. The stability of the latter species is thus dependent on the hydrophobicity of the pyridinium end group and follows the order of pyridinium < 2-picolinium ≈ 3-picolinium < 4-dimethylaminopyridinium << 4-*tert*-butylpyridinium. In terms of the electronic repulsions between two neighbouring CB[7] hosts in a 2:1 complex, the largest effects might be expected in the guests with the shorter ethyl bridge. This appears to hold true in the cases of BPE^{2+} *vs* BPH^{2+} and $BAPE^{2+}$ vs. $BAPH^{2+}$, however the value of $K_{2:1}$ for $BBPE^{2+}$ vs. $BBPH^{2+}$ (and $BBPX^{2+}$) follows an opposite trend with slightly more stable complexes with the shorter ethyl linker than with the hexyl (or *p*-xylyl) linker (Table 1).

Experimental

Materials

The cucurbit[7]uril was prepared by the method of Day and co-workers.[2b] The bis(pyridinium)alkane dibromide salts were prepared by heating a mixture of an excess of the appropriate substituted pyridine (pyridine, 2-picoline, 3-picoline, 4-dimethylaminopyridine, or 4-*tert*-butylpyridine (typically 15–30 mmol, Aldrich)) with 1,2-dibromoethane, 1,6-dibromohexane, or α,α-dibromo-*p*-xylene (typically 4–5 mmol Aldrich) in 50 mL of acetonitrile (15 mL of DMF for reaction with 2-picoline) at 70 °C for 24 hr. The precipitate was washed with methanol, followed by ether and then recrystallized from methanol/ether mixtures.

1,2-Bis(1-pyridinium)ethane dibromide ([BPE]Br_2). Yield: 26%, mp 240–245 °C. ^{1}H NMR (D_2O, 400 MHz) δ 8.82 (d, 4H, H2, $J = 5.6$ Hz), 8.66 (t, 2H, H4, $J = 8.0$ Hz), 8.12 (t, 4H, H3, $J = 6.0$ Hz), 5.32 (s, 4H, Hα) ppm. ^{13}C NMR (D_2O) δ 147.59 (C4), 144.76 (C2), 129.23 (C3), 60.16 (Cα) ppm. HR-ESIMS calcd for $C_{12}H_{14}N_2$ $[M - 2Br]^{2+}$ $m/z = 93.0573$; found 93.0571.

1,2-Bis(4-dimethylamino-1-pyridinium)ethane dibromide ([BAPE]Br_2). Yield: 38%, mp > 300 °C (Lit. 301 °C (dec),[23] >300 °C (dec)[24]). ^{1}H NMR (D_2O, 400 MHz) δ 7.74 (d, 2H, H2, $J = 7.2$ Hz), 6.79 (d, 2H, H3, $J = 7.2$ Hz), 4.56 (s, 4H, Hα), 3.15 (s, 2H, CH_3) ppm. ^{13}C NMR (D_2O, 100 MHz) δ 156.46 (C2), 141.05 (C3), 56.72 (Cα), 39.60 (CH_3) ppm. HR-ESIMS calcd for $C_{16}H_{24}N_2$ $[M - 2Br]^{2+}$ $m/z = 136.0994$; found 136.0995.

1,2-Bis(4-*tert*-butyl-1-pyridinium)ethane dibromide ([BPPE]Br_2). Yield: 29%, mp > 300 °C (Lit.[25] > 300 °C). ^{1}H NMR (D_2O, 400 MHz) δ 8.51 (d, 4H, H2, $J = 6.5$ Hz), 8.00 (d, 4H, H3, $J = 6.5$ Hz), 5.12 (s, 4H, Hα), 1.38 (s, 18H, CH_3) ppm. ^{13}C NMR (D_2O, 125 MHz) δ 174.37 (C4), 144.05 (C2), 126.66 (C3), 59.70 (Cα), 36.76 (C_{tert}), 29.39 (CH_3) ppm. HR-ESIMS calcd for $C_{20}H_{30}N_2$ $[M - 2Br]^{2+}$ $m/z = 149.1199$; found 149.1199.

1,6-Bis(1-pyridinium)hexane dibromide ([BPH]Br_2). Yield: 93%, mp 140–143 °C. ^{1}H NMR (D_2O, 400 MHz) δ 8.80 (d, 4H, H2, $J = 5.6$ Hz), 8.62 (t, 2H, H4, $J = 8.0$ Hz), 8.03 (t, 4H, H3, $J = 7.2$ Hz), 4.57 (t, 4H, Hα, $J = 7.4$ Hz) 1.99 (m, 4H, Hβ), 1.37 (m, 4H, Hγ) ppm. ^{13}C NMR (D_2O) δ 145.62 (C4), 144.20 (C2), 128.26 (C3), 61.73 (Cα), 30.29 (Cβ), 24.81 (Cγ) ppm. HR-ESIMS calcd for $C_{16}H_{22}N_2$ $[M - 2Br]^{2+}$ $m/z = 121.0886$; found 121.0881.

1,6-Bis(2-methyl-1-pyridinium)hexane dibromide ([B2PH]Br_2). Yield: 15%, mp 230–235 °C. ^{1}H NMR (D_2O) δ 8.66 (d, 2H, H_6, $J = 6.4$ Hz), 8.33 (t, 2H, H4, $J = 8.0$ Hz), 7.87 (d, 2H, H3, $J = 8.0$ Hz), 7.81 (t, 2H, H5, $J = 6.4$ Hz), 4.49 (t, 4H, Hα, $J = 7.9$ Hz), 2.80 (s, 6H, CH_3), 1.93 (m, 4H, Hβ), 1.46 (m, 4H, Hγ) ppm. ^{13}C NMR (D_2O, 125 MHz) δ 155.63 (C2), 145.42 (C4), 145.07 (C6), 130.61 (C3), 125.98 (C5), 58.19 (Cα), 29.54 (Cβ), 25.50 (Cγ), 19.89 (CH_3) ppm HR-ESIMS calcd for $C_{18}H_{26}N_2$ $[M - 2Br]^{2+}$ $m/z = 135.1042$; found 135.1043.

1,6-Bis(3-methyl-1-pyridinium)hexane dibromide ([B3PH]Br_2). Yield: 55%, mp 157–162 °C. ^{1}H NMR (D_2O, 400 MHz) δ 8.62 (s, 2H, H2), 8.57 (d, 2H, H6, J = 6.0 Hz), 8.30 (d, 2H, H4, J = 8.0 Hz), 7.87 (t, 2H, H5, J = 7.0 Hz), 4.49 (t, 4H, Hα, J = 7.9 Hz), 2.48 (s, 6H, CH_3), 1.94 (m, 4H, Hβ), 1.32 (m, 4H, Hγ) ppm. ^{13}C NMR (D_2O, 100 MHz) δ 145.98 (C4), 143.66 (C2), 141.23 (C6), 139.91 (C3), 127.39 (C5), 61.45 (Cα), 30.24 (Cβ), 24.78 (Cγ), 17.60 (CH_3) ppm. HR-ESIMS calcd for $C_{18}H_{26}N_2$ $[M - 2Br]^{2+}$ m/z = 135.1042; found 135.1043.

1,6-Bis(4-dimethylamino-1-pyridinium)hexane dibromide ([BAPH]Br_2). Yield: 80%, mp 275–276 °C. ^{1}H NMR (D_2O, 400 MHz) δ 7.92 (d, 2H, H2, J = 7.6 Hz), 6.80 (d, 2H, H5, J = 7.6 Hz), 4.05 (t, 4H, Hα, J = 7.0 Hz), 3.14 (s, 12H, CH_3), 1.78 (m, 4H, Hβ), 1.25 (m, 4H, Hγ) ppm. ^{13}C NMR (D_2O, 100 MHz) δ 156.29 (C4), 141.25 (C2), 107.47 (C3), 57.46 (Cα), 39.33 (CH_3), 29.68 (Cβ), 24.83 (Cγ) ppm. HR-ESIMS calcd for $C_{20}H_{32}N_2$ $[M - 2Br]^{2+}$ m/z = 164.1308; found 164.1309.

1,6-Bis(4-*tert*-butyl-1-pyridinium)hexane dibromide ([BBPH]Br_2). Yield: 74%, mp 274–277 °C. (Lit.[26] 299–300 °C). ^{1}H NMR (D_2O, 500 MHz) δ 8.63 (d, 4H, H2, J = 7.0 Hz), 8.01 (d, 4H, H3, J = 7.0 Hz), 4.49 (t, 4H, Hα, J = 7.2 Hz) 1.95 (m, 4H, Hβ), 1.36 (s, 18H, CH_3), 1.34 (m, 4H, Hγ) ppm. ^{13}C NMR (D_2O, 125 MHz) δ 171.96 (C4), 143.67 (C2), 125.74 (C3), 61.00 (Cα), 36.32 (Ct), 30.59 (Cβ), 29.49 (CH_3), 25.18 (Cγ) ppm. HR-ESIMS calcd for $C_{24}H_{38}N_2$ $[M - 2Br]^{2+}$ m/z = 177.1512; found 177.1514.

α,α′-Bis(4-*tert*-butyl-1-pyridinium)-*p*-xylene dibromide ([BBPX]Br_2). Yield: 89%. mp > 300 °C. ^{1}H NMR (D_2O) δ 8.66 (d, 4H, H2, J = 5.6 Hz), 8.01 (d, 4H, H3, J = Hz), 7.44 (s, 4H, H2′), 5.72 (s, 4H, Hα), 1.33 (s, 18H, CH_3) ppm. ^{13}C NMR (D_2O, 125 MHz) δ 172.72 (C4), 143.93 (C2), 134.98 (C1′), 130.11 (C2′), 126.03 (C3), 63.30 (CH_2), 36.44 (Ct), 29.45 (CH_3). HR-ESIMS calcd for $C_{26}H_{34}N_2$ $[M - 2Br]^{2+}$ m/z = 187.1355; found 187.1356.

Methods

The ^{1}H and ^{13}C NMR spectra were recorded on a Bruker Avance 400 and 500 instrument in D_2O and the resonance assignments were confirmed using 2D COSY, HMBC, and HMQC experiments. The 1:1 and 2:1 CB[7] host-guest stability constants were determined from ^{1}H NMR competition studies at 25 °C in D_2O containing 0.050 mol dm^{-3} acetate buffer (0.050 mol dm^{-3} NaOAc-d_3/0.025 mol dm^{-3} DCl, pD = 4.75). For the 1:1 complexes, the ratio of CB[7]:guest:competitor was generally 3:4:4, with 3–4 mmol dm^{-3} CB[7]. For the 2:1 complexes, the CB[7]:guest:competitor was generally 6:4:3, with 6–8 mmol dm^{-3} CB[7], using a competitor with a lower CB[7] binding constant than that of the CB[7] binding to the 1:1 host-guest. It is assumed in the calculations under these conditions that the 1:1 species is essentially fully formed. The competitor guests used were 3-(trimethylsilyl)propionic acid ($K_{CB[7]}$ = (1.82 ± 0.22) × 10^7 dm^3 mol^{-1}),[2b] benzyltrimethylammonium bromide ((2.5 ± 0.6) × 10^8 dm^3 mol^{-1}),[10] *p*-xylenediamine ((1.84 ± 0.34) × 10^9 dm^3 mol^{-1}),[2b] 1-(trimethylammonio)methylferrocene iodide ((3.31 ± 0.62) × 10^{11} dm^3 mol^{-1}),[10] tetramethylammonium bromide ((1.2 ± 0.4) × 10^5 dm^3 mol^{-1}),[10] and tetraethylammonium bromide ((1.0 ± 0.2) × 10^6 dm^3 mol^{-1}).[10] The UV spectra were recorded on a Hewlett-Packard 8452A diode-array spectrometer using 1.00 cm pathlength quartz cells. The electrospray mass spectra were obtained on a QstarXL MS/MS system, with an ESI source, with the samples prepared in distilled water. The energy-minimization calculations (Fig. 1) were carried out with the MM2 program in the Chem3D Pro (Version 11.0.1, CambridgeSoft) software.

Conclusions

A series of 1:1 (including [2]pseudorotaxanes) and 2:1 host-guest complexes may be formed between cucurbit[7]uril as and dicationic α,ω-bis(pyridinium)alkane chains in aqueous solution. The relative 1:1 and 2:1 host-guest stability constants are related to the natures of the cationic head groups and the alkyl linkers. The CB[7] cyclic component in the [2]pseudorotaxane may be moved along the dicationic thread to one of the end groups by the complexation by a second CB[7] host on other end group.

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