Chapter 5

Bis(m-phenylene)-32-Crown-10-Based Cryptands, Powerful Hosts for Paraquat Derivatives

5.1. INTRODUCTION

Self-assembled structures are attractive to materials science for their reversibility at the molecular level, and therefore for their ability to correct structural defects, an option unavailable for traditional, covalently bonded systems. However, in order for a self-assembling, non-covalent system to possess properties sufficient to compete with covalently bonded polymers, it must exhibit a strong association between its components. Paraquat derivatives (N,N'-dialkyl-4,4'-biyridinium salts) have been widely used as guests in supramolecular chemistry to construct numerous complexes with large crown ethers, such as bis(m-phenylene)-32-crown-10 derivatives and bis(p-phenylene)-34-crown-10 derivatives. With the aim to prepare large supramolecular systems efficiently from small building blocks, we are interested in improving complexation of paraquats by design of optimized hosts. Here, by synthesizing four new cryptands and studying their complexation with paraquat derivatives, we address two questions. First, why are cryptands better hosts for paraquat derivatives than the corresponding simple crown ethers? Second, can we further improve complexation by introducing more and/or better binding sites?
5.2. RESULTS AND DISCUSSION

A. Design of Cryptands.

We reported that cryptand 3a exhibited a 100-fold increase in association constant \( (K_a) \) for paraquat derivatives 2 relative to crown ether 1a. The enhanced association in the case of 3a is due to the preorganization of the host. This was confirmed by the thermodynamic study of four complexes based on 1c, 1d, 2a, 2b, and 3a (Table 1). Interestingly, the enthalpies of binding of crowns 1c and 1d are comparable to or larger than that of cryptand 3a, but the entropic penalties for the crown ethers are much larger than for the cryptand. As expected the cryptand 3a undergoes significantly less structural change in the analogous process and this is the major factor in its enhanced binding strength.
Table 1. Association constants\(^{a}\) and thermodynamic parameters\(^{b}\) for complexes of paraquat derivatives (2a and 2b) with crown ethers (1c and 1d) and a cryptand (3a).

<table>
<thead>
<tr>
<th>Complex</th>
<th>(K_a \times 10^{-2}) (M(^{-1}))</th>
<th>(\Delta G_{294})(^{c}) (kJ/mol)</th>
<th>(\Delta H_a)(^{d}) (kJ/mol)</th>
<th>(\Delta S_a)(^d) (J/mol(\cdot)deg)</th>
</tr>
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<tbody>
<tr>
<td>3a•2a</td>
<td>6.0 × 10(^2)</td>
<td>-25</td>
<td>-48</td>
<td>-78</td>
</tr>
<tr>
<td>3a•2b</td>
<td>6.0 × 10(^2)</td>
<td>-25</td>
<td>-54</td>
<td>-97</td>
</tr>
<tr>
<td>1c•2b</td>
<td>2.7 ± 0.5</td>
<td>-14</td>
<td>-48</td>
<td>-117</td>
</tr>
<tr>
<td>1d•2b</td>
<td>3.5 ± 0.5</td>
<td>-14</td>
<td>-56</td>
<td>-144</td>
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</table>

\(a\). Measured at 21\(^\circ\)C; average of 5 solutions with the constant host concentration and varying guest concentrations ([guest]\(_0\) : [host]\(_0\) = 1-50). \(K_a\) values of complexes of 3a were determined before\(^5a\) and the same method was used for complexes of 2b using the time averaged signals for H\(_2\) of 1c and 1d.

\(b\). Determined by variable temperature \(^1\)H NMR spectroscopy in acetone-\(d_6\) and van’t Hoff plots using the time averaged signals for H\(_1\) of 3a and H\(_2\) of 1c and 1d.

\(c\). Estimated error: ±5% relative.

\(d\). Measured from 21-50\(^\circ\)C; estimated errors: < 10% relative.

This is consistent with the X-ray analysis results that bis\((m\)-phenylene\)-32-crown-10 (1a) is not folded in the solid state,\(^3a\) but it and its derivative 1b are folded in crystalline complexes with paraquat 2a (Figure 1a),\(^5a\) a paraquat derivative,\(^3e\) and a diammonium salt.\(^7\) Formation of pseudocryptands using ditopic counterions, such as trifluoroacetate,\(^8\) water,\(^9a\) or trifluoroacetate and water together,\(^9b\) to hydrogen bond the OH groups of 1b\(^8,9a\) or 1c,\(^9b\) is also effective in increasing association constants for such “taco complexes”.
Our continuing design of improved paraquat hosts is based on careful examination of the X-ray structures. Note from the structure of the cryptand complex 3a•2a (Figure 1b) the lack of direct interaction of the guest with the third ethyleneoxy chain of 3a. Rather the β-pyridinium hydrogens of 2a are bound to a water molecule that bridges to the ether oxygen atoms of the third ethyleneoxy chain. Moreover, in crown ether based 1b•2a (Figure 1a) an F atom of the PF$_6$ counterion is H-bonded to the β-pyridinium hydrogens of 2a. On the basis of these observations we designed new cryptands 3b and 3c with an H-bond acceptor site, the pyridyl nitrogen, in approximately the proper location for interaction with the β-pyridinium hydrogens of 2a. In 3b the third linker between the phenylene rings contains nine atoms, while in 3c it contains only seven atoms. The pyridine ring of 3b is affected by the electron withdrawing carbonyl groups, while that of 3c is more electron-rich because of the CH$_2$O substituents. Cryptand 3d has the same length of the third bridge as cryptand 3c, but 3d has no additional binding site on the third bridge. Comparison of the complexation of these two cryptands with paraquat will reveal the importance of the additional binding site. Cryptand 3e was prepared with the aim to optimize the length of the third bridge; the number of atoms in the third bridge of cryptands 3b, 3c, 3d, and 3e is 9, 7, 7, and 8, respectively. Thus, these structures address two issues: geometry and intrinsic H-bonding ability of the host.

Figure 1. X-ray structures of 1b•2a (a) and 3a•2a (b).

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B. Syntheses of Cryptands, 3b, 3c, 3d, and 3e.

All four new cryptands, 3b, 3c, 3d, and 3e, were prepared using the pseudo-high dilution technique. Bis(1,3,5-phenylene)di(1’,4’,7’,10’,13’-pentaoxatridecyl)[2’’,6’’-di(methyleneoxy)carbonyl]pyridine] (3b) was synthesized from bis(5-hydroxymethyl-1,3-phenylene)-32-crown-10¹⁰ (1b) and 2,6-pyridinedicarbonyl dichloride. Bis-(1,3,5-phenylene)di(1’,4’,7’,10’,13’-pentaoxatridecyl)(2’’,6’’-dioxymethylene)pyridine (3c) was made from bis(5-hydroxy-1,3-phenylene)-32-crown-10⁵a (1e) and 2,6-bis(bromomethyl)pyridine. Bis(1,3,5-phenylene)di(1’,4’,7’,10’,13’-pentaoxatridecyl)[3’’,5’’-di(methyleneoxy)benzyl alcohol] (3d) was prepared from bis(5-bromomethyl-1,3-phenylene)-32-crown-10¹⁰ (1e) and 3,5-dihydroxybenzyl alcohol. Bis(1,3,5-phenylene)di(1’,4’,7’,10’,13’-pentaoxatridecyl)[1’’,4’’-di(methyleneoxy)benzene] (3e) was prepared from 1e and hydroquinone.

C. Complexation of the New Cryptands with paraquat (2a).

For each of the four new cryptands 3b, 3c, 3d, and 3e, a 1.00 mM equimolar acetone solution of the cryptand and 2a is yellow due to charge transfer between electron-rich aromatic rings of the cryptand host and electron-poor pyridinium rings of the guest 2a. Job plots¹¹ (Figure 2) based on proton NMR data demonstrated that all four complexes were of 1:1 stoichiometry in solution.
Figure 2. Job plots showing the 1:1 stoichiometries of the complexes between 3b and 2a (a), between 3c and 2a (b), between 3d and 2a (c), and between 3e and 2a (d) in CD$_3$COCD$_3$. (a) $[3b]_0 + [2a]_0 = 1.00$ mM; (b) $[3c]_0 + [2a]_0 = 2.00$ mM; (c) $[3d]_0 + [2a]_0 = 2.00$ mM; (d) $[3e]_0 + [2a]_0 = 2.00$ mM. $[2a]_0$, $[3b]_0$, $[3c]_0$, $[3d]_0$, and $[3e]_0$ are initial concentrations of 2a, 3b, 3c, 3d, and 3e. Delta = chemical shift change for H$_1$ of 3b, 3c, 3d, and 3e.
The association constant $K_a$ for the complexation between $3b$ and $2a$, a fast-exchange system, was determined to be $5.0 \pm 2.0 \times 10^6 \text{ M}^{-1}$ in acetone-$d_6$ at 22 °C. using a competitive complexation method recently developed by Smith group. This value is one of the highest for association constants of paraquat complexes. $K_a$ values for the other complexes are summarized in Table 2. Compared with the $K_a$ value of $1a\cdot 2a$, the complex based on the simple crown ether, $K_a$ values of cryptand complexes $3b\cdot 2a$, $3c\cdot 2a$, $3d\cdot 2a$, and $3e\cdot 2a$ increased about 9000, 17, 11, and 40 times, respectively.

Table 2. Association constants in acetone-$d_6$ for complexes of paraquat $2a$ with crown ether $1a$ and different cryptands at 22 °C.

<table>
<thead>
<tr>
<th></th>
<th>$1a\cdot 2a$</th>
<th>$3b\cdot 2a$</th>
<th>$3c\cdot 2a$</th>
<th>$3d\cdot 2a$</th>
<th>$3e\cdot 2a$</th>
</tr>
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<tbody>
<tr>
<td>$K_a \times 10^{-3} \text{ (M}^{-1})$</td>
<td>0.55 (+0.05)</td>
<td>$5.0 \pm 2.0 \times 10^3$</td>
<td>9.4 (+0.9)</td>
<td>6.3 (+0.6)</td>
<td>22 (+2)</td>
</tr>
</tbody>
</table>

$a. K_a$ of complex $1a\cdot 2a$ was reported before.14

The improvement from crown ether complex $1a\cdot 2a$ to cryptand complexes $3d\cdot 2a$ and $3e\cdot 2a$ can be mainly attributed to the preorganization of the cryptand hosts, while the improvement from $3d\cdot 2a$ to $3c\cdot 2a$ is due to the introduction of an additional binding site, the pyridyl nitrogen atom. The great increase in association constant from crown ether complex $1a\cdot 2a$ to pyridyl ester cryptand complex $3b\cdot 2a$ is a result of the combination of the preorganization of the host and the introduction of an additional binding site. The increase in association constant from pyridyl ether cryptand (7-atom link) complex $3c\cdot 2a$ to hydroquinone cryptand (8-atom link) complex $3e\cdot 2a$ and to pyridyl ester cryptand (9-atom link) complex $3b\cdot 2a$ indicates that nine is an appropriate number of atoms on the third bridge of the cryptand host for the best complexation of paraquat derivatives.


The X-ray crystal structures of pyridyl ester cryptand $3b$ and paraquat $2a$ are shown in Figures 3a and 3b and that of their complex $3b\cdot 2a$ is shown in Figure 3c. No solvent molecules were found in the structure of $3b$. The two phenylene rings of $3b$ are
not parallel to each other but exhibit a twist angle of 36°. The centroid-centroid distance between them is 6.68 Å. Most notably, in accord with our design, a β-pyridinium hydrogen of the guest is directly H-bonded to the pyridine nitrogen atom of the host in 3b•2a (E). That is, the pyridine nitrogen atom of 3b in 3b•2a is at almost the same position as the oxygen atom of the water bridge in 3a•2a and the fluorine atom of a PF6− anion in 1b•2a (Figure 1). On the other side of 2a, both β-pyridinium hydrogens are hydrogen-bonded to the oxygen atom of an acetone molecule (A and B). Just like 3a•2a (Figure 1b), 3b•2a is stabilized by two hydrogen bonds involving α-pyridinium hydrogens (C and J). However, N-methyl hydrogens are not involved in hydrogen bonding in 3a•2a, but there is one hydrogen bond involving a methyl hydrogen in 3b•2a (I). One possible reason for this difference is that the third bridge (9 atoms) of 3b is shorter than that (13 atoms) of 3a and this allows the guest to be closer to the ethyleneoxy links. Further stabilization forces are four indirect hydrogen bonds (D, F, G, and H in Figure 3c) between 3b and 2a based on two acetone bridges. The two oxygen atoms on the acetone bridges are hydrogen bonded to different phenyl hydrogens of the cryptand (D and H) and the same α-pyridinium hydrogen (F and G). Comparison of the crystal structures of 3b and 3b•2a (Figures 3b and 3c) shows that the conformation of the host does not change much during complexation because of its preorganization. Therefore, the enhanced affinity of 3b for 2a is attributable to its preorganization and the properly located additional binding site.

It is not surprising that, just like 3a•2a, 3b•2a is also stabilized by face-to-face π-stacking interactions. For maximizing π-stacking interactions between the cryptand host 3b and the paraquat guest 2a, the aromatic rings of 3b are almost parallel, with an angle of 7.4° and a centroid-centroid separation of 7.19 Å while the corresponding values are 9.8° and 6.94 Å in 3a•2a; the paraquat guest 2a lies nearly parallel to and nearly symmetrically between the two phenylene rings of 3b.
Figure 3. X-ray structures of 2a (a), 3b (b), and 3b•2a (c). Oxygens are green, nitrogens are yellow, acetone molecules are black, 3b is red, and 2a is blue. (a) Two PF$_6^-$ ions have been omitted for clarity. (b) and (c) Hydrogens of 3b, the other solvent molecules, and PF$_6^-$ ions have also been omitted for clarity. Hydrogen-bond parameters: C···O(N) distances (Å), H···O(N) distances (Å), C-H···O(N) angles (deg) A, 3.33, 2.35, 166; B, 3.22, 2.38, 141; C, 3.05, 2.08, 163; D, 3.53, 2.57, 162; E, 3.22, 2.37, 142; F, 2.84, 2.53, 97.0; G, 2.99, 2.50, 110; H, 3.52, 2.57, 157; I, 3.42, 2.61, 138; J, 3.41, 2.48, 155. Face-to-face $\pi$-stacking parameters: centroid-centroid distances (Å) 3.82, 4.15, 4.25, 4.53; ring plane/ring plane inclinations (deg): 5.4, 2.8, 12.6, 5.0.
E. Solid State Structure of [3]Complex 3c•2a•3c.

Though the complex between pyridyl ether cryptand 3c and 2a has 1:1 stoichiometry in solution as shown above and the gaseous state as shown below and the molar ratio of host:guest in the mother solution for the crystal growth was 1:2, the complex between 3c and 2a have 2:1 stoichiometry in the solid state (Figure 4). 3c•2a•3c is similar to two recently reported pseudorotaxane-like complexes, 3a•2a•3a and 3f•2a•3f, in that each paraquat unit is shared by two cryptand moieties and the dihedral angle between two pyridinium rings of the paraquat guest is zero. However, in 3c•2a•3c two N-methyl hydrogens are involved in hydrogen bonding to the hosts (Q), while no N-methyl hydrogens in 3a•2a•3a and 3f•2a•3f are involved in hydrogen bonding. Also in 3c•2a•3c there are two acetonitrile molecules, while in 3a•2a•3a there are two water molecules and in 3f•2a•3f from the smaller cryptand 3f there are no solvent molecules. Notably again, the pyridyl nitrogen atom is hydrogen bonded to the β-pyridinium hydrogen atoms in 3c•2a•3c (M and N). It appears that the 2:1 complex maximizes H-bonding in the solid state; it produces 4 α-pyridinium to host (O and P), 4 bifurcated β-pyridinium to host (M and N), 2 methyl to host (Q), 2 methyl to acetonitrile (K), and 2 α-pyridinium to acetonitrile H-bonds (L). In solution presumably some of these pyridinium hydrogens can interact with solvent molecules so the complex between 3c and 2a has the 1:1 stoichiometry.

CPK model studies suggest that when 1:1 complexes are formed, the pyridine nitrogen of cryptand 3b is at a better position to form hydrogen bonds with the β-pyridinium hydrogens of the paraquat derivatives than that of 3c, because of the difference in the third bridge lengths-9 atoms for 3b and 7 atoms for 3c. Furthermore, when forming 1:1 complexes with paraquat derivatives, the two phenylene rings of the smallest host 3c can not be parallel to each other because of the shorter third bridge, while those of 3b can do so. This makes face-to-face π-stacking interactions weaker in 3c•2a than in 3b•2a. These factors lead to an 840-fold increase in the value of apparent association constant from 3c•2a to 3b•2a even though the pyridine ring of 3c is presumably a better donor than that of 3b.
Figure 4. Two views of the X-ray structure of 3c•2a•3c. Oxygens are green, nitrogens are yellow, 3c is red, 2a is blue, and acetonitrile molecules are magenta. The other solvent molecules, two PF_6^- ions, and hydrogens except the ones on 2a have been omitted for clarity. Hydrogen-bond parameters: C···O(N) distances (Å), H···O(N) distances (Å), C-H···O(N) angles (deg) K, 3.49, 2.56, 161; L, 3.41, 2.53, 157; M, 3.55, 2.61, 175; N, 3.31, 2.38, 168; O, 3.07, 2.51, 118; P, 3.35, 2.45, 162; Q, 3.32, 2.50, 143. Face-to-face π-stacking parameters: centroid-centroid distances (Å) 3.85, 4.16; ring plane/ring plane inclinations (deg): 8.9, 15.5. The centroid-centroid distance (Å) and dihedral angle (deg) between the pyridinium rings of 2a: 4.27 and 0.

As shown by its crystal structure (Figure 5), 3d•2a is stabilized by H-bonding and face-to-face π-stacking interactions. However this complex has some unique characteristics which were not observed in previously reported 1:1 cryptand/paraquat complexes\textsuperscript{5a,15} and 3b•2a. Firstly, the paraquat guest 2a is threaded unsymmetrically into the cavity of the 32-crown-10 part of the cryptand host in 3d•2a (Figure 5), while the paraquat unit is nearly symmetrically located in all other reported 1:1 cryptand/paraquat complexes\textsuperscript{5a,15} and 3b•2a. The unsymmetrical orientation in 3d•2a results from H-bonding of one of the α-hydrogens of 2a with the benzyl ether oxygen of 3d (S of Figure 5) and intercomplex H-bonding (see below and Figure 6). Secondly, due to the unsymmetrical threading, the phenylene rings of the 32-crown-10 part are face-to-face π-stacked with only one pyridinium ring of the guest (Figures 5 and 6), while in all other reported 1:1 cryptand/paraquat complexes\textsuperscript{5a,15} and 3b•2a the phenylene rings are face-to-face π-stacked with both pyridinium rings of the guest. Thirdly, the dihedral angle, 21.4°, between the pyridinium rings (Figure 5) is the largest among reported 1:1 cryptand/paraquat complexes\textsuperscript{5a,15} and 3b•2a. This angle is zero in 2a (Figure 1a) and its other 2:1 cryptand complexes.\textsuperscript{14} This big change in the angle presumably occurs in order to maximize the hydrogen-bonding between 3d and 2a; three of the four α-pyridinium hydrogens are H-bonded (R, S, T, and U). None of the β-pyridinium hydrogens are bound to the host’s ethyleneoxy chains (see below, however), while in the other cryptand/paraquat complexes at least one β-pyridinium hydrogen is bound to the host’s ether oxygen atoms directly or indirectly.\textsuperscript{5a,14,15}
**Figure 5.** X-ray structure of 3d•2a. Oxygens are green, hydrogens are magenta, 3d is red, and 2a is blue. An acetone molecule, two PF$_6^-$ ions, and hydrogens except the ones on 2a and the hydroxy group of 3d have been omitted for clarity. Hydrogen-bond parameters: C···O distances (Å), H···O distances (Å), C-H···O angles (deg) R, 3.14, 2.54, 119; S, 3.11, 2.45, 123; T, 3.23, 2.26, 162; U, 3.14, 2.50, 122. Face-to-face π-stacking parameters: centroid-centroid distances (Å) 3.68, 4.28; ring plane/ring plane inclinations (deg): 7.9, 10.7. The centroid-centroid distance (Å) and dihedral angle (deg) between the pyridinium rings of 2a: 4.27 and 21.3.

In the solid state, the complex is arranged linearly to form a supramolecular polycomplex by nesting each complex in the cleft of the next, resulting in an alternating pattern of orientation (Figure 6). The stabilization forces between complex monomers are two hydrogen bonds between the oxygen atom of the hydroxyl group of the cryptand host of one complex and two β-pyridinium hydrogens on one side of the paraquat guest of the neighboring complex.
Figure 6. Ball-stick (a) and cartoon (b) representations of the 3d·2a packing structure. (a) Hydrogens are blue, nitrogens are black, and oxygens are green. Three acetone molecules, six PF₆⁻ ions, and hydrogens except the ones on 2a and hydroxy groups of 3d have been omitted for clarity. Hydrogen-bonding parameters: C···O distances (Å), H···O distances (Å), C-H···O angles (deg) V, 3.26, 2.43, 141; W, 3.30, 2.31, 177. (b) 3d molecules are red, and 2a molecules are blue.

In the X-ray structure (Figure 7a) of hydroquinone-based cryptand 3e, two crystallographically independent molecules were found. One is disordered and the other is not. An acetone molecule is located in the cavity of each molecule. The phenylene rings in both structures are almost parallel to each other with small dihedral angles of 5.0° and 5.1°. This is different from the crystal structure (Figure 3b) of pyridyl ester cryptand 3b, in which the phenylene rings are twisted with an angle of 36°. The centroid-centroid distances of the phenylene rings of both structures are almost the same, 7.20 Å and 7.23 Å.

Figure 7. X-ray structures of 3e. 3e molecules are red and acetone molecules are black. Other solvent molecules and hydrogens have been omitted for clarity. The centroid-centroid distances (Å) and dihedral angles (deg) between the phenylene rings of the two 3e molecules: 7.20 and 5.0 for the left one and 7.23 and 5.1 for the right one.

Bright yellow crystals of 3e•2a are visually very nice, but they are not single and do not give clean diffraction patterns. Only a preliminary crystal structure was obtained (see Supporting Information). However, it is obvious that the complex between 3e and 2a has a 1:1 stoichiometry in the solid state and the guest 2a is threaded into the cavity of the 32-crown-10 part of the cryptand host 3e, similarly to complex 3d•2a.
H. Mass Spectrometric Characterization of Cryptand Complexes.

The 1:1 stoichiometries of the complexes based on the four new cryptands and paraquat 2a were confirmed by electrospray ionization mass spectrum (ESIMS). We observed two peaks for 3b•2a using a solution of 3b and 2a in 4:1 acetonitrile:chloroform: m/z 1058 [3b•2a - PF₆]⁺ (50%) and 457 [3b•2a - 2PF₆]²⁺ (100%) (Figure 8). The same peaks but with different relative intensities were found in methanol: m/z 1058 [3b•2a - PF₆]⁺ (18%) and 457 [3b•2a - 2PF₆]²⁺ (20%) (base peak at m/z 186 corresponding to [2a - 2PF₆]⁺).

The following peaks were detected for 3c•2a using a solution of 3c and 2a in methanol: m/z 1147 [3c•2a]⁺ (0.5%), 1058 [3c•2a - HPF₆ + K + H₂O]⁺ (2%), 1002 [3c•2a - PF₆]⁺ (4%), and 429 [3c•2a - 2PF₆]²⁺ (2%) (base peak at m/z 331 corresponding to [2a - PF₆]⁺).

Three peaks were observed for 3d•2a using a solution of 3d and 2a in methanol: m/z 1031 [3d•2a - PF₆]⁺ (6%), 927 [3d•2a - 2PF₆ + K]⁺ (2%), and 452 [3d•2a - 2PF₆ + H₂O]²⁺ (1%) (base peak at m/z 331 corresponding to [2a - PF₆]⁺).

Two peaks were observed for 3e•2a using a solution of 3e and 2a in 4:1 acetonitrile:chloroform: m/z 1001 [3e•2a - PF₆]⁺ (14%) and 428 [3e•2a - 2PF₆]²⁺ (100%).
Figure 8. Electrospray mass spectrum of a solution of 3b and 2a in a mixture of acetonitrile and chloroform (4:1).

The very strong binding ability of pyridyl ester cryptand 3b for paraquat derivatives was emphatically confirmed by FABMS of a solution of 3b and 2b (1:1 molar ratio) (Figure 9). The base peak at \(m/z = 1119\) corresponds to \([3b \cdot 2b \cdot PF_6]^+\); the next peak at \(m/z = 974\) of 55% intensity corresponds to \([3b \cdot 2b - 2PF_6]^+\), and the cryptand signal at \(m/z = 728\) constitutes only 35% in intensity!! No any other pseudorotaxane has revealed such a preponderance of the complex in its mass spectrum to our knowledge.
Figure 9. Fast-atom bombardment mass spectrum of an acetone solution of 2b and 3b (1:1 molar ratio). The matrix is GLY.

I. Electrostatic Potential Maps of Cryptand Hosts and Guest 2a at the AM1 Level.

Electrostatic potential maps (Figure 10) of 2a, 3b, 3c, 3d, and 3e at the AM1 level were determined with the CAChe program. It is obvious that paraquat guest 2a is very electron-poor, while the cryptand hosts have electron-rich cavities, so strong charge-transfer interactions can form between the cryptand host and paraquat guest when any of these cryptand hosts is put into acetone with 2a. All hydrogens, including methyl hydrogens, on paraquat 2a have very low electron density so they want to form hydrogen-bonds with electron-rich atoms, such as ether oxygen atoms and pyridyl nitrogen atoms, on the cryptand hosts. In solution some of these hydrogens can interact with solvent molecules and the rest with the host, resulting in 1:1 stoichiometry for these cryptand/paraquat complexes. In the solid state, no or not enough solvent molecules are available to interact with these acidic hydrogens so hydrogen bonds are provided by the hosts in 2:1 stoichiometry. This is probably the main reason for the formation of 2:1 complexes (3a•2a•3a, 3c•2a•3c, and 3f•2a•3f) between cryptand hosts and paraquat in the solid state. The pyridyl nitrogen atoms of 3b and 3c are electron-rich (Figures 10b and 10c), so they are good hydrogen-bonding acceptors for hydrogens on paraquat.
**Figure 10.** Electrostatic potential maps of 2a (a), 3b (b), 3c (c), 3d (d), and 3e (e) at the AM1 level as determined with the CAChe program.
5.3. CONCLUSIONS

It has been demonstrated that bis\((m\text{-phenylene})\)32-crown-10 based cryptands are powerful hosts for paraquat derivatives compared with the simple crown ether host. The significant improvement in complexation is the result of the combination of the preorganization of the cryptand hosts and the introduction of additional and optimized binding sites. Specifically, pyridyl ester cryptand 3\(b\), which has a pyridyl nitrogen atom located at a site occupied by either water or a PF\(_6\) anion in analogous complexes, exhibited the highest association constant \(K_a = 5.0 \times 10^6\) M\(^{-1}\) in acetone with paraquat, 9000 times greater than the crown ether system. These readily accessible cryptands are valuable host structures in the construction of larger supramolecular systems. Currently, we are focusing on these projects.

5.4. EXPERIMENTAL SECTION

**General Procedures.** Dimethylformamide (DMF) was distilled under reduced pressure. Other chemicals were reagent grade and used as received. All solvents were HPLC or GC grade. NMR solvents were bought from Cambridge Isotope Laboratories and used as received. The NMR spectra were recorded on a Varian Unity or Inova Instrument. Low-resolution electron impact mass spectroscopy (LREIMS) was carried out on VG-Quohro 4000 (direct probe inlet) Triple Quadrupole Mass Spectrometer. Low-resolution fast-atom bombardment mass spectroscopy (LRFABMS) and high-resolution fast-atom bombardment mass spectroscopy (HRFABMS) was carried out on HX110 Dual Focusing Mass Spectrometer using xenon gas for ionization. Low-resolution electrospray ionization mass spectroscopy (LRESIMS) of 3\(b\)•2\(a\), 3\(c\)•2\(a\), and 3\(d\)•2\(a\) in methanol were performed by HT Laboratories of San Diego, CA. LRESIMS of 3\(b\)•2\(a\) and 3\(c\)•2\(a\) in 4:1 acetonitrile:chloroform were carried out on a local TSQ Finnigan LC/MS/MS instrument. Melting points were taken in capillary tubes and are uncorrected. Elemental analyses were performed by Atlantic Microlabs of Norcross, GA.

**Complexation Studies by Proton NMR.** All solutions were prepared as follows. Precisely weighed amounts of dried hosts and guests were added into separate screw cap
vials. The solvent was added with to-deliver volumetric pipets. Then specific volumes of each fresh solution were mixed to yield the desired concentrations. For example, in order to make three solutions, 0.500 mM 3e/1.00 mM 2a, 0.500 mM 3e/3.00 mM 2a, and 0.500 mM 3e/5.00 mM 2a, a 1.00 mM solution of 3e was made first by adding 5.00 mL acetone-\(d_6\) with a 5.00 mL to-deliver pipette into a screw cap vial containing 3.35 mg (0.00500 mmol) of 1. Then 0.300 mL of this solution was added with a 0.300 mL to-deliver pipet to three vials that contained 0.300 mL of 2.00 mM, 0.300 mL of 6.00 mM, and 0.300 mL of 10.0 mM of 2a separately. \(^1\)H NMR data were collected on a temperature controlled spectrometer. Acetone-\(d_6\) was chosen as the NMR solvent because all compounds used here have relatively good solubilities in it. Error bars were calculated based on a 0.05 mg deviation in weight, a 0.001 ppm deviation in chemical shift on proton NMR spectra, and a \(\pm 2\%\) deviation in fractional complexation (\(\Delta/\Delta_0\)). Standard errors in both the intercept and slope coefficients based on regression were used to determine errors in association constants.

**Bis(1,3,5-phenylene)di(1',4',7',10',13'-pentaoxatridecyl)\(\text{[2''',6''']-di(methyleneoxycarbonyl)}\)pyridine (unoptimized synthesis of 3b).** To a stirred solution of 1 mL pyridine and 200 mL CH\(_3\)CN under N\(_2\) \(1\text{b}^{10}\) (0.50 g, 0.84 mmol) in 25 mL of CH\(_3\)CN was added dropwise at approximately the same rate as 0.17 g (0.84 mmol) of 2,6-pyridinedicarbonyl dichloride in 25 mL CH\(_3\)CN. The reaction mixture was stirred for 1 h after addition of the reactants. The solvent was removed by rotoevaporation to give a white solid, which was dissolved in 40 mL of CHCl\(_3\), and washed with water (3 \(\times\) 40 mL) and 5\% NaHCO\(_3\) (3 \(\times\) 40 mL). The organic layer was evaporated to dryness using a rotoevaporator, producing a yellow viscous oil. Column chromatography (silica gel, 9:1 chloroform:acetone) was employed to isolate 3b. Recrystallization from EtOAc-hexane provided 20 mg (3.3\%, which is low for this kind of reaction; a higher yield is expected now because we made a 3b derivative in 21\% yield\(^{15b}\)) of 3b, mp 153.5–155.3 \(^\circ\)C. \(^1\)H NMR (400 MHz, CDCl\(_3\), 22 \(^\circ\)C) \(\delta\) (ppm): 8.37 (d, 2H, \(J = 7.8\) Hz), 8.05 (t, 1H, \(J = 7.8\) Hz), 6.56 (d, 4H, \(J = 2.1\) Hz), 6.47 (t, 2H, \(J = 2.1\) Hz), 5.33 (s, 4H), 3.94 (m, 8H), 3.76 (m, 8H), and 3.65 (m, 16H). \(^{13}\)C NMR (100 MHz, CDCl\(_3\), 22 \(^\circ\)C) \(\delta\) (ppm): 164.880, 160.033, 148.252, 138.201, 137.245, 128.150, 106.325, 102.168, 70.960, 70.755, 69.640,
Bis-(1,3,5-phenylene)di(1',4',7',10',13'-pentaoxatridecyl)(2''',6'''-dioxymethyleneypyridine) (3c). A solution of 700 mg (1.23 mmol) of 1c and 326 mg (1.46 mmol) of 2,6-bis(bromomethyl)pyridine in 30 mL DMF was added at 0.75 mL/h into a suspension containing 2.07 g (15.0 mmol) of K₂CO₃ and 5.00 mg of (n-Bu)₄NI in 400 mL DMF under N₂ at 110 °C. After addition, the reaction mixture was stirred at 110 °C for 10 days, cooled and rotoevaporated. The residue was treated with CHCl₃ and filtered. Removal of CHCl₃ afforded a crude product that was purified by flash column chromatography (Et₂O increasing to EtOAc) to give 340 mg (41%) of 3c, a pale yellow oil. ¹H NMR (400 MHz, CDCl₃, 22 °C) δ (ppm): 7.75 (t, 1H, J = 7.8 Hz), 7.37 (d, 2H, J = 7.8 Hz), 6.12 (t, 2H, J = 2.1 Hz), 6.07 (d, 4H, J = 2.1 Hz), 5.21 (s, 4H), 3.91 (s, 8H), 3.73 (t, 8H, J = 4.4 Hz), and 3.62 (s, 16H). ¹H NMR (400 MHz, CD₃COCD₃, 22 °C) δ (ppm): 7.84 (t, 1H, J = 7.8 Hz), 7.47 (d, 2H, J = 7.8 Hz), 6.12 (d, 4H, J = 2.1 Hz), 6.06 (t, 2H, J = 2.1 Hz), 5.19 (s, 4H), 3.94 (t, 8H, J = 4.4 Hz), 3.66 (t, 8H, J = 4.4 Hz), and 3.52 (m, 16H). LREIMS m/z 671 [M + H]⁺, 672 [M]⁺; HRFABMS (NBA/PEG) m/z calcd for [M + H]⁺ C₃₅H₄₆O₁₂N, 672.3020; found 672.2991, error 4.3 ppm.

Synthesis of Bis(1,3,5-phenylene)di(1’,4’,7’,10’,13’-pentaoxatridecyl)[3’’,5’’-di(methyleneoxy)benzyl alcohol] (3d). A solution of 0.66 g (0.91 mmol) of 1e and 0.13 g (0.90 mmol) of 3,5-dihydroxybenzyl alcohol in 40 mL of DMF was added at 0.75 mL/h to a suspension containing K₂CO₃ (1.7 g, 12 mmol) and TBAI (5.00 mg) in 400 mL of DMF at 110 °C. After complete addition, the mixture was stirred at 110 °C for 5 days, evaporated to remove DMF, treated with dichloromethane, and filtered. Removal of dichloromethane afforded a crude product, which was purified by flash column chromatography using ethyl acetate:methanol (9:1) to afford pure 3d as a white solid (0.27 g, 42%). mp 120.3-122.2 °C. ¹H NMR (400 MHz, CDCl₃, 22 °C) δ (ppm): 6.63 (4H, d, J = 2.0 Hz), 6.32 (2H, t, J = 2.0 Hz), 6.28 (2H, d, J = 2.0 Hz), 6.09 (1H, t, J = 2.0 Hz), 5.01 (4H, s), 4.63 (2H, d, J = 6.2 Hz), 3.94 (8H, m), 3.81 (8H, m), 3.65 (16H, s), and
2.01 (1H, t, J = 6.2 Hz). LRFABMS (NBA) m/z 723.4 [M + Na]\(^+\), 700.3 [M]\(^+\), 683.3 [M-OH]\(^+\); HRFABMS (NBA/PEG) m/z calcd for [M]\(^+\) C\(_{37}\)H\(_{48}\)O\(_{13}\), 700.3095, found 700.3088, error 0.9 ppm.

**Synthesis of Bis(1,3,5-phenylene)di(1',4',7',10',13'-pentaoxatridecyl)[1'',4''-di(methyleneoxy)benzene] (3e).** A solution of 360 mg (0.500 mmol) of 1e and 50.0 mg (0.500 mmol) of hydroquinone in 40 mL DMF was added via a syringe pump at 1.00 mL/h into a suspension containing 3.20 (23.0 mmol) g of potassium carbonate and 2.00 mg of tetrabutylammonium iodide in 150 mL DMF at 110 °C. After complete addition, the reaction mixture was stirred at 110 °C for further 5 days. The cooled mixture was evaporated to remove DMF, treated with chloroform, and filtered. Removal of chloroform afforded a crude product. The crude product was purified by flash column chromatography eluting with ethyl acetate to afford 3e as a white solid, 142 mg (42%). mp 98.1.5-99.0 °C. \(^1\)H NMR (400 MHz, CDCl\(_3\), 22 °C) \(\delta\) (ppm): 6.67 (4H, s), 6.52 (4H, d, J = 2.4 Hz), 6.41 (2H, t, J = 2.4 Hz), 5.04 (4H, s), 4.07 (8H, t, J = 4.2 Hz), 3.81 (8H, t, J = 4.2 Hz), and 3.68 (16H, s). LRFABMS (NBA) m/z 671.3 [M + H]\(^+\); HRFABMS (NBA/PEG) m/z calcd for [M]\(^+\) C\(_{36}\)H\(_{47}\)O\(_{12}\), 670.2989, found 670.2976, error 2.0 ppm.

**Determination of the association constant \((K_{a,3b•2a})\) for 3b•2a.** The association constant \((K_{a,3b•2a})\) for 3b•2a was determined using a competitive NMR method recently developed by Smith Group.\(^\text{12}\) 1,1'-Ethylene-2,2'-dipyridinium bis(hexafluorophosphate) (“diquat” 7) was used as the reference guest. In a 0.670 mM equimolar acetone-\(d_6\) solution of reference host 3a, cryptand 3b, and guest 7, the concentration of complexed 3a, [3a]c, was 0.174 mM. \(K_{a,3b•7}\) was thus determined to be 3.30 (± 0.66) \(\times\) \(10^5\) M\(^{-1}\). The error is based on errors of [3a]c and \(K_{a,3a•7}\), which was determined using the method discussed below for the determination of \(K_{a,3c•2a}, K_{a,3d•2a},\) and \(K_{a,3e•2a}\). Then, in a 0.500 mM equimolar acetone-\(d_6\) solution of guest 2a, cryptand host 3b, and 7, the concentration of complexed reference guest 7, [7]c, was 0.102 mM. \(K_{a,3b•2a}\) was thus determined to be 5.0 (± 2.0) \(\times\) \(10^6\) M\(^{-1}\). The error is based on errors of [7]c and \(K_{a,3b•7}\).

**Determination of association constants \((K_{a,3c•2a}, K_{a,3d•2a},\) and \(K_{a,3e•2a}\)) for 3c•2a, 3d•2a, and 3e•2a.** \(K_{a,3c•2a}, K_{a,3d•2a},\) and \(K_{a,3e•2a}\) were determined in the same way. Here the determination of \(K_{a,3c•2a}\) is given as an example. \(^1\)H NMR characterizations were done
on solutions with constant [3c] and varied [2a]. Based on these NMR data, \( \Delta_{0,3c} \), the difference in \( \delta \) values for H1 of 3c in the uncomplexed and fully complexed species, was determined by the extrapolation of a plot of \( \Delta = \delta - \delta_0 \) vs. \( 1/[2a]_0 \) in the high initial concentration range of 2a. Then \( K_{a,3c\cdot2a} \) was calculated from 

\[
K_{a,3c\cdot2a} = \left( \frac{\Delta_{3c}}{\Delta_{0,3c}} \right) / \left\{ 1 - \left( \frac{\Delta_{3c}}{\Delta_{0,3c}} \right) \right\} \left[ \frac{[2a]_0 - (\Delta_{3c}/\Delta_{0,3c})[3c]_0}{[2a]_0} \right].
\]

The \( \Delta_{0,3} \) values for 3c•2a, 3d•2a, and 3e•2a were determined to be 0.599 ppm, 0.604 ppm, and 0.701 ppm in acetone, respectively. The error of \( K_{a,3c\cdot2a} \) is based on experimentally observed 2% variation in \( \Delta/\Delta_0 \) values over the range 0.2 - 0.8.

**X-ray analysis of 2a.** Colorless crystals of 2a were grown by vapor diffusion of pentane into its acetone solution. X-Ray diffraction experiment was carried out on a Bruker Apex CCD diffractometer equipped with MoK\(_\alpha\) radiation (\( \lambda = 0.71073 \) Å) and a graphite monochromator. Data were collected from \( \theta = 2.38^\circ \) to \( \theta = 24.99^\circ \) by using phi and omega scans. SADABS\(^1\) absorption corrections were applied. The structure was solved by direct methods and refined by full-matrix least squares procedure on \( F^2 \) using the SHELXTL.\(^2\) Non-hydrogen atoms were refined with anisotropic displacement coefficients, and hydrogen atoms were treated as idealized contributions. Crystal data: rod, colorless, 0.50 \( \times \) 0.10 \( \times \) 0.10 mm\(^3\), C\(_{12}\)H\(_{14}\)F\(_{12}\)N\(_2\)P\(_2\), FW 476.19, orthorhombic, space group \( Pnma \), \( a = 14.4612(16) \) Å, \( b = 11.6741(13) \) Å, \( c = 10.6275(11) \) Å, \( \alpha = \beta = \gamma = 90^\circ \), \( V = 1794.2(3) \) Å\(^3\), \( Z = 4 \), \( D_c = 1.763 \) g cm\(^{-3}\), \( T = 218 \) K, \( \mu = 3.62 \) cm\(^{-1}\), 10268 measured reflections, 1664 independent reflections, 139 parameters, \( F(000) = 752 \), \( R_1 = 0.0757 \), \( wR_2 = 0.1816 \) (all data), \( R_1 = 0.0674 \), \( wR_2 = 0.1753 \) [I > 2\( \sigma(I) \)], max. residual density 0.498 e\( \cdot \)Å\(^{-3}\), max./min. transmission 0.9647/0.8397, and goodness-of-fit (\( F^2 \)) = 1.113.

**X-ray analysis of 3b.** Colorless crystals of 3b were grown by slow evaporation of a 9:1 chloroform:acetone solution of 3b. X-Ray diffraction data were collected on a Siemens Bruker P4 diffractometer by the omega scan method in a range 2.0\(^\circ\) \( \leq \theta \leq 25.0^\circ\). SADABS absorption corrections were applied. The structure was solved by direct methods and refined by full-matrix least squares procedure on \( F^2 \) using the SHELXTL. Non-hydrogen atoms were refined with anisotropic displacement coefficients, and hydrogen atoms were treated as idealized contributions. Crystal data: block, colorless, 0.60 \( \times \) 0.40 \( \times \) 0.30 mm\(^3\), C\(_{37}\)H\(_{45}\)NO\(_{14}\), FW 727.74, Monoclinic, space group \( C_2/c \), \( a = \)
17.688(3), \( b = 11.184(2), c = 18.034(5) \, \text{Å}, \beta = 96.030(14) ^\circ, V = 3547.9(18) \, \text{Å}^3, Z = 4, D_c = 1.362 \, \text{g cm}^{-3}, T = 241\, \text{K}, \mu = 1.05 \, \text{cm}^{-1}, 3555 \) measured reflections, 2931 independent reflections \([R(\text{int}) = 0.0464], 236 \) parameters, \( F(000) = 1544, R_1 = 0.1490, \, wR_2 = 0.2873 \) (all data), \( R_1 = 0.0867, \, wR_2 = 0.2060 \) \([I > 2\sigma(I)]\), maximum residual density 0.436 e•Å\(^{-3}\), and goodness-of-fit \((F^2) = 1.573.

**X-ray analysis of 3b•2a.** Bright yellow crystals of 3b•2a were grown by vapor diffusion of pentane into an acetone solution of 3b and 2a (1:1). X-Ray diffraction data were collected on an Oxford Diffraction XCalibur2™ diffractometer equipped with the Enhance X-ray Source™ (MoK\(\alpha\) radiation; \(\lambda = 0.71073 \, \text{Å}\)) and a Sapphire 2™ CCD detector by the phi and omega scan method in a range \(1.06 ^\circ \leq \theta \leq 27.50 ^\circ\). The structure was solved by the direct methods using SIR\(^{18}\) and refined by full-matrix least squares using Crystals.\(^{19}\) Crystal data: prism, yellow, \(0.38 \times 0.20 \times 0.12 \, \text{mm}^3\), \(C_{58}H_{77}F_{12}N_{3}O_{17}P_{2}\), \(FW 1378.18\), monoclinic, space group \(P2_1/c\), \(a = 13.9159(17)\, \text{Å}, \quad b = 21.217(2), \quad c = 21.768(2) \, \text{Å}, \quad \beta = 95.423(9) ^\circ, \quad V = 6398.3(12) \, \text{Å}^3, \quad Z = 4, \quad D_c = 1.431 \, \text{g cm}^{-3}, \quad T = 100\, \text{K}, \quad \mu = 1.73 \, \text{cm}^{-1}, 82374 \) measured reflections, \(20876 \) independent reflections \([R(\text{int}) = 0.03], 829 \) parameters, \(F(000) = 2880.000, R_1 = 0.1950, \, wR_2 = 0.1524 \) (all data), \( R_1 = 0.0618, \, wR_2 = 0.1223 \) \([I > 2\sigma(I)]\), maximum residual density 1.32 e•Å\(^{-3}\), and goodness-of-fit \((F^2) = 0.9244.

**X-ray analysis of 3c•2a•3c.** Yellow crystals of 3c•2a•3c were grown by vapor diffusion of pentane into a 1:1 acetonitrile:acetone solution of 3c and 2a (1:2 molar ratio). X-Ray diffraction data were collected on a Bruker Apex CCD diffractometer equipped with MoK\(\alpha\) radiation \((\lambda = 0.71073 \, \text{Å}\)) and a graphite monochromator by the phi and omega scan method in a range \(1.06 ^\circ \leq \theta \leq 28.28 ^\circ\). SADABS absorption corrections were applied. The structure was solved by direct methods and refined by full-matrix least squares procedure on \(F^2\) using the SHELXTL. Non-hydrogen atoms were refined with anisotropic displacement coefficients, and hydrogen atoms were treated as idealized contributions. Besides the main 3c•2a•3c molecule in the crystal structure there are two acetonitrile, water and acetone solvent molecules. The acetone molecule is disordered around a center of symmetry and was treated by SQUEEZE.\(^{20}\) Correction of the X-ray data by SQUEEZE (38 e/cell) was close to the required values (32 e/cell). Crystal data:
block, yellow, 0.45 × 0.30 × 0.20 mm³, C_{46.50}H_{63}F_6N_4O_{13.50}P, FW 1038.98, triclinic, space group P-1, a = 10.3991(6), b = 13.6159(8), c = 19.3423(12) Å, α = 87.7590(10)°, β = 82.5240(10)°, γ = 72.6750(10)°, V = 2592.3(3) Å³, Z = 2, D_c = 1.331 g cm⁻³, T = 100K, µ = 1.40 cm⁻¹, 19230 measured reflections, 11808 independent reflections [R(int) = 0.0229], 622 parameters, F(000) = 1094, R₁ = 0.0954, wR² = 0.2265 (all data), R₁ = 0.0710, wR² = 0.2084 [I > 2σ(I)], maximum residual density 0.816 e•Å⁻³, and goodness-of-fit (F²) = 1.067.

**X-ray analysis of 3d•2a.** Bright yellow crystals of 3d•2a were grown by vapor diffusion of pentane into an acetone solution of 3d and 2a (1:1). X-ray diffraction data were collected in a range 2.5 o ≤ θ ≤ 25.0 o on a Nonius KappaCCD diffractometer equipped with MoKa radiation (λ = 0.71073 Å), a graphite monochromator, and an Oxford Cryostream chiller. The structure was solved by the direct method SIR and refined by full-matrix least squares using Crystals. Nonhydrogen atoms were treated anisotropically and hydrogen atoms were placed in calculated positions. 9851 reflections were used in refinements by full-matrix least-squares on F². Crystal data: Prism, yellow, 0.25 × 0.20 × 0.12 mm³, C_{52}H_{68}F_{12}N_2O_{14}P_2, FW 1235.04, monoclinic, space group P2₁/c, a = 11.871(3), b = 23.066(5), c = 20.450(6) Å, β = 90.307(8)°, V = 5599.5(25) Å³, Z = 4, D_c = 1.465 g cm⁻³, T = 100 K, µ = 1.84 cm⁻¹, 68453 measured reflections, 9851 independent reflections, 739 parameters, F(000) = 2576, R₁ = 0.1427, wR² = 0.1674 (all data), R₁ = 0.0588, wR² = 0.0891 [I > 4σ(I)], max. residual density 0.96 e•Å⁻³, max./min. transmission 0.979/0.940, and goodness-of-fit (F²) = 1.1035.

**X-ray analysis of 3e.** Colorless crystals of 3e were grown by slow evaporation of an acetone solution of 3e at room temperature. The chosen crystal was mounted on a nylon CryoLoop™ (Hampton Research) with Krytox® Oil (DuPont) and centered on the goniometer of a Oxford Diffraction XCalibur2™ diffractometer equipped with a Sapphire 2™ CCD detector. The data collection routine, unit cell refinement, and data processing were carried out with the program CrysAlis. The structure was solved by direct methods and refined using the SHELXLXTL program package. The asymmetric unit of the structure comprises two crystallographically independent molecules of 3e, three acetone molecules, and 2.93 water molecules. Successful refinement of the structure was
plagued by disorder in one arm of a 3e molecule, the acetone molecules, and additional residual electron density that was modeled as water. The arm of the 3e molecule was modeled as adopting two conformations that refined to occupancies of 0.528(3) and 0.472(3). The disordered acetone was modeled as adopting two conformations with occupancies of 0.578(7) and 0.422(7). Four strong residual electron density peaks, all within 2.7-3.0 Å of other oxygen atoms were presumed to be the oxygen atoms of water molecules. Two of these Fourier peaks were refined as fully occupied oxygen sites. The remaining two Fourier peaks could not have full occupancy due to their close proximity to the disordered 3e arm, and refined to occupancies 0.432(9) and 0.50(1). The size of the anisotropic thermal parameters in the remaining two acetone molecules as well as the prevalence of residual electron density peaks near the molecules suggest additional disorder which was not modeled successfully. The final refinement involved an anisotropic model for all non-hydrogen atoms and a riding model for all hydrogen atoms. A total of six hydrogen atoms from the disordered 3e molecule, three from the disordered acetone and the hydrogen atoms of the water molecules were all absent from the model.

Crystal data: plate, colorless, 0.48 × 0.24 × 0.085 mm³, 2C₃₆H₄₆O₁₂•3C₃H₆O•2.93H₂O, FW 1568.48, triclinic, space group P-1, a = 10.7938(13), b = 20.2260(19), c = 21.431(2) Å; α = 63.096(9)°, β = 83.239(10)°, γ = 84.292(9)°; V = 4137.6(7) Å³, Z = 2, Dc = 1.259 g cm⁻³, T = 100 K, μ = 0.96 cm⁻¹, 22982 measured reflections, 14609 independent reflections[R(int) = 0.0234], 1100 parameters, F(000) = 1683, R₁ = 0.0889, wR₂ = 0.2076 (all data), R₁ = 0.0699, wR₂ = 0.1926 [I > 2σ(I)], and GooF (F²) = 1.109.

Calculations of electrostatic potential maps of 2a, 3b, 3c, 3d, and 3e at AM1 level with the CAChe program. CAChe WorkSystem Pro Version 6.1 was used in the calculations of electrostatic potential maps of 2a, 3b, 3c, 3d, and 3e. The structures of these compounds were inputted from their individual crystal structures (2a, 3b, and 3e) or paraquat complex crystal structures (3c•2a•3c and 3d•2a). Then their electrostatic potential maps at AM1 level were calculated under AM1 geometry using the AM1 wavefunction
5.5. ACKNOWLEDGEMENTS

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5.6. SUPPORTING INFORMATION

*The preliminary crystal structure of 3e•2a*

Bright yellow crystals of 3e•2a were grown by vapor diffusion of pentane into an acetone solution of 2a with excess 3e. The structure was solved by the direct method SIR$^\text{S1}$ in Crystals.$^{21}$ Data were collected in a range $1.06^\circ \leq \theta \leq 27.50^\circ$ on an Oxford
Diffraction XCalibur™ diffractometer equipped with the Enhance X-ray Source™ (MoKα radiation; λ = 0.71073 Å) and a Sapphire 2™ CCD detector by the phi and omega scan method.

Electrospray mass spectrum of a solution of 3b and 2a in methanol


S1

C$_{30}$H$_4$O$_{10}$
Electrospray mass spectrum of a solution of 3c and 2a in methanol

Electrospray mass spectrum of a solution of 3d and 2a in methanol

Electrospray mass spectrum of a solution of 3e and 2a in a mixture of acetonitrile and chloroform (4:1)

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Abstract: Four new bis(m-phenylene)-32-crown-10 based cryptands with different third bridges were prepared. The complexes between them and paraquat derivatives were studied by proton NMR spectroscopy, mass spectrometry, and X-ray analysis. It was found that these cryptands bind paraquat derivatives very strongly. Specifically, a diester cryptand with a pyridyl nitrogen atom located at a site occupied by either water or a PF₆ anion in analogous complexes exhibited the highest association constant $K_a = 5.0 \times 10^6$ M$^{-1}$ in acetone with paraquat, 9000 times greater than the crown ether system. X-ray structures of this and analogous complexes demonstrate that improved complexation with this host is a consequence of preorganization, adequate ring size for occupation by the guest and the proper location of the pyridyl N-atom for binding to the $\beta$-pyridinium hydrogens of the paraquat guests. This readily accessible cryptand is one of the most powerful hosts reported for paraquats.