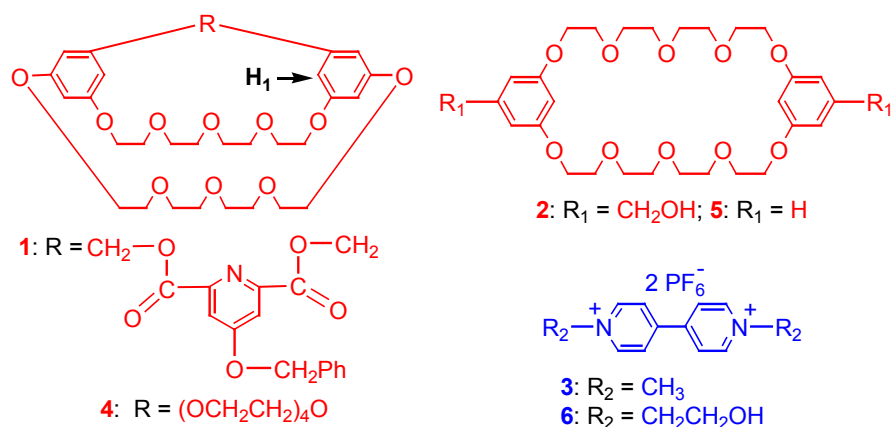


Chapter 11

Formation of Dimers of Inclusion Cryptand/Paraquat Complexes Driven by Dipole-Dipole and Face-to-Face π -Stacking Interactions

11.1. INTRODUCTION

Supramolecular chemistry, chemistry beyond the covalent bond, aims at developing sophisticated chemical systems by molecular recognition, self-replication, and self-organization of components based on noncovalent interactions.¹ The study of dimers of supramolecular complexes is important and active due to their potential applications, including molecular muscles,² daisy chains,³ nanoscale magnets,⁴ capsules,⁵ and host-guest complexation.⁶ The main driving force for formation of almost all of these dimers is hydrogen bonding, though other driving forces such as metal coordination^{5a,b} and multiple ionic interactions^{5c} were also reported. However, to the best of our knowledge, dimers of complexes based on dipole-dipole or face-to-face π -stacking interactions have been rarely reported. This is surprising considering the wide study of these interactions in supramolecular chemistry.⁷ Here we report the formation of two new dimers of inclusion complexes driven by dipole-dipole and face-to-face π -stacking interactions.



11.2. RESULTS AND DISCUSSION

Complexation of cryptand and pseudocryptand hosts with viologen (paraquat) derivatives has been studied in our group in order to prepare large supramolecular systems.⁸ Recently, in order to add another binding site, we made new functionalized cryptand **1** by cyclization of bis(*m*-phenylene)-32-crown-10 derivative **2**⁹ and 4-benzyloxypyridine-2,6-dicarbonyl dichloride.¹⁰ A 1.00 mM equimolar acetone solution of **1** and **3** is yellow due to charge transfer between electron-rich aromatic rings of **1** and electron-poor pyridinium rings of **3**. The stoichiometry of the complex between **1** and **3** was determined to be 1:1 in solution by a Job plot¹¹ (Fig. 1) using proton NMR data. The association constant (K_a) for the complexation between **1** and **3** was determined by a competitive method¹² to be $9.0 (\pm 1.8) \times 10^5 \text{ M}^{-1}$, an increase of 1600 times from $5.5 (\pm 0.5) \times 10^2 \text{ M}^{-1}$ for the complex based on the simple crown ether **5** and **3**.^{8d}

Electrospray ionization mass spectrometry (ESIMS) of solutions of **1** with **3** or **6** confirmed the 1:1 stoichiometry of the complexation and the existence of dimers of cryptand/paraquat complexes. Two relevant peaks were found for **1•3** (Fig. 2): m/z 1164.5 (51%) [**1•3** - PF₆]⁺ and 509.9 (100%) [**1•3** - 2PF₆]²⁺. Five weaker peaks were consistent with (**1•3**)₂ (Fig. 2): m/z 1196.5 (4%) [(**1•3**)₂ - HPF₆ - C₆H₆ - H]²⁺, 1120.6 (3%) [(**1•3**)₂ - 2PF₆ - C₇H₇ - CH₃ + H₂O]²⁺, 1057.5 (2%) [(**1•3**)₂ - 3PF₆ - C₇H₇ + Na]²⁺, 969.5 (3%) [(**1•3**)₂ - 2PF₆ - 2HPF₆ - C₇H₇ - 2CH₃ + Na]²⁺, and 526.2 (7%) [(**1•3**)₂ - PF₆ - 2HPF₆ - C₆H₅]⁴⁺. Three relevant peaks were found for **1•6**: m/z 1224 (87%) [**1•6** - PF₆]⁺, 927 (100%) [**1•6** - PF₆ - HPF₆ - CH₂CH₂OH - OCH₂C₆H₅]⁺ and 661 (41%) [**1•6** - OH -

CH₂OH]²⁺. Two weaker peaks were consistent with (**1•6**)₂: *m/z* 714 (7.6%) [(**1•6**)₂ - 4PF₆ - H₂O]³⁺ and 708 (17%) [(**1•6**)₂ - 4PF₆ - 2H₂O]³⁺. Interestingly the strong peak at *m/z* 888 (76%) appears to be due to the [3]complex **1₂•6** [**1₂•6** - 2PF₆ - CH₂OH - OCH₂C₆H₅]²⁺; this is noteworthy because in several cases analogous (cryptand)₂•paraquat complexes have been isolated and characterized.^{8d} Another possible contribution to this peak is from the dimer (**1•6**)₂: [(**1•6**)₂ - **1** - 2PF₆ - CH₂OH - OCH₂C₆H₅]²⁺. ESIMS of a solution of **1** provided no evidence of the dimer **1₂**. Thus, we inferred that involvement of the pyridyl nitrogen in hydrogen bonding to polarize the benzyloxypyridine moiety is a prerequisite for dimerization of **1•3** and **1•6**.

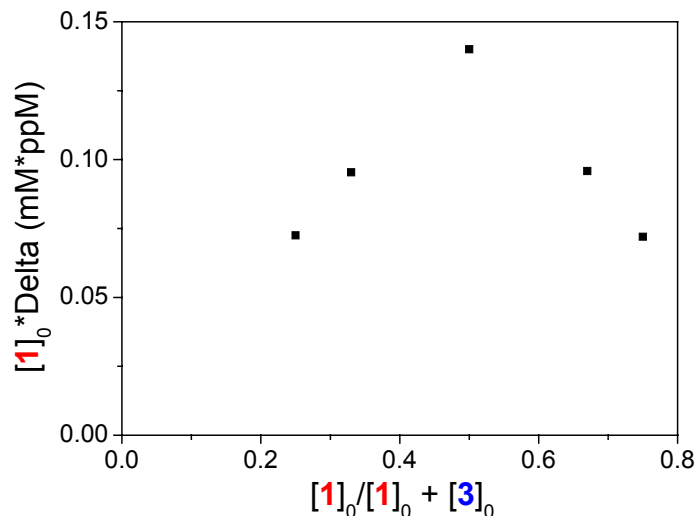


Figure 1. Job plot showing the 1:1 stoichiometry of the complex between **1** and **3** in CD₃COCD₃ solution. [1]₀ + [3]₀ = 1.00 mM. Delta = the chemical shift change of H₁.

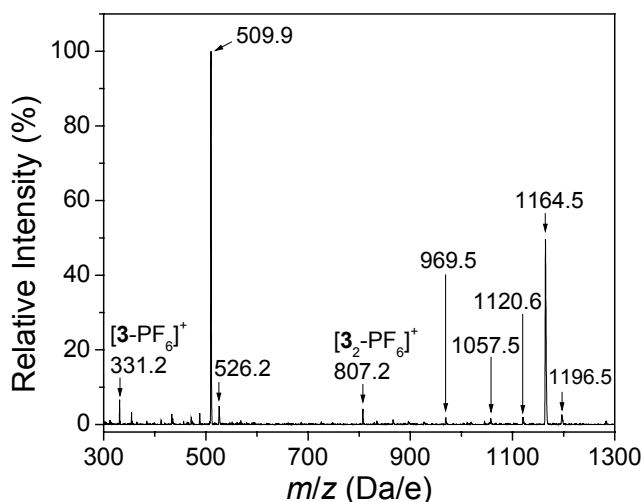


Figure 2. Partial ^1H NMR spectra (400 MHz, 2.5:1 acetone- d_6 :chloroform- d , 22 °C) of (a) 1.11 mM undried **3** (5.00 mM water), (b) 1.11 mM undried **3** and 2.29 mM **2** (5.50 mM water), (c) 1.11 mM undried **3** and 2.29 mM **1** (5.50 mM water), (d) 1.11 mM dried **3** and 2.29 mM **1** (1.38 mM water), (e) 2.29 mM **1** (0.50 mM water) and (f) 1.11 mM dried **3** and **2** (1.50 mM water).

The formation of the dimer (**1**·**3**)₂ was confirmed by X-ray analysis of a single crystal prepared by the vapor diffusion of pentane into an acetone solution of **3** and excess **1**. **1**·**3** is stabilized by hydrogen bonding and face-to-face π -stacking interactions in the solid state (Fig. 3). As designed, H-bonding of the pyridyl N with the β -H of **3** (**b**) adds stability.

Dimer formation is driven by dipole-dipole and face-to-face π -stacking interactions (Fig. 4). The pyridine ring of **1** is electron-poor due to the electron-withdrawing effects of the two carbonyl substituents and hydrogen bonding of its nitrogen atom with a β -pyridinium hydrogen of the electron-poor guest **3**. Therefore, the relatively electron-rich phenyl ring of **1** forms a dipole with the pyridine ring. In dimer two dipoles are arranged in opposite directions to allow π - π interactions between donor-acceptor pairs. The centroid-centroid distances and ring plane/ring plane dihedral angle for these

face-to-face π -stacking interactions are smaller than the above discussed interactions between the electron-rich phenylene rings of **1** and the electron-poor pyridinium rings of **3**. This demonstrates that the face-to-face π -stacking interactions here are strong.

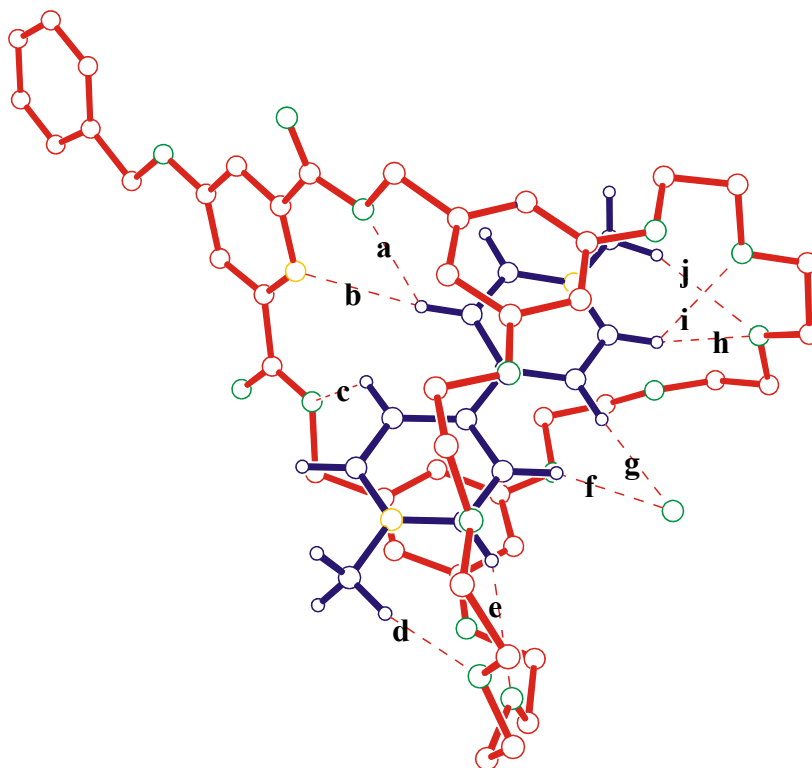


Figure 3. X-ray structure of **1·3**. Oxygens are green, **1** is red, **3** is blue, and nitrogens are yellow. Solvent molecules, two PF₆ counterions, and hydrogens except the ones on **3** have been omitted for clarity. Selected hydrogen-bond parameters: C-O(N) distances (Å) **a** = 3.22, **b** = 3.62, **c** = 3.38, **d** = 3.41, **e** = 3.32, **f** = 3.37, **g** = 3.28, **h** = 3.33, **i** = 3.14, **j** = 3.56; H···O(N) distances (Å) **a** = 2.52, **b** = 2.68, **c** = 2.70, **d** = 2.44, **e** = 2.58, **f** = 2.43, **g** = 2.29, **h** = 2.37, **i** = 2.60, **j** = 2.62; C-H···O(N) angles (deg) **a** = 127, **b** = 157, **c** = 126, **d** = 164, **e** = 130, **f** = 158, **g** = 174, **h** = 161, **i** = 114, **j** = 157. Face-to-face π -stacking parameters: centroid-centroid distances (Å) 3.73, 3.91; ring plane/ring plane inclinations (deg): 7.6, 5.0.

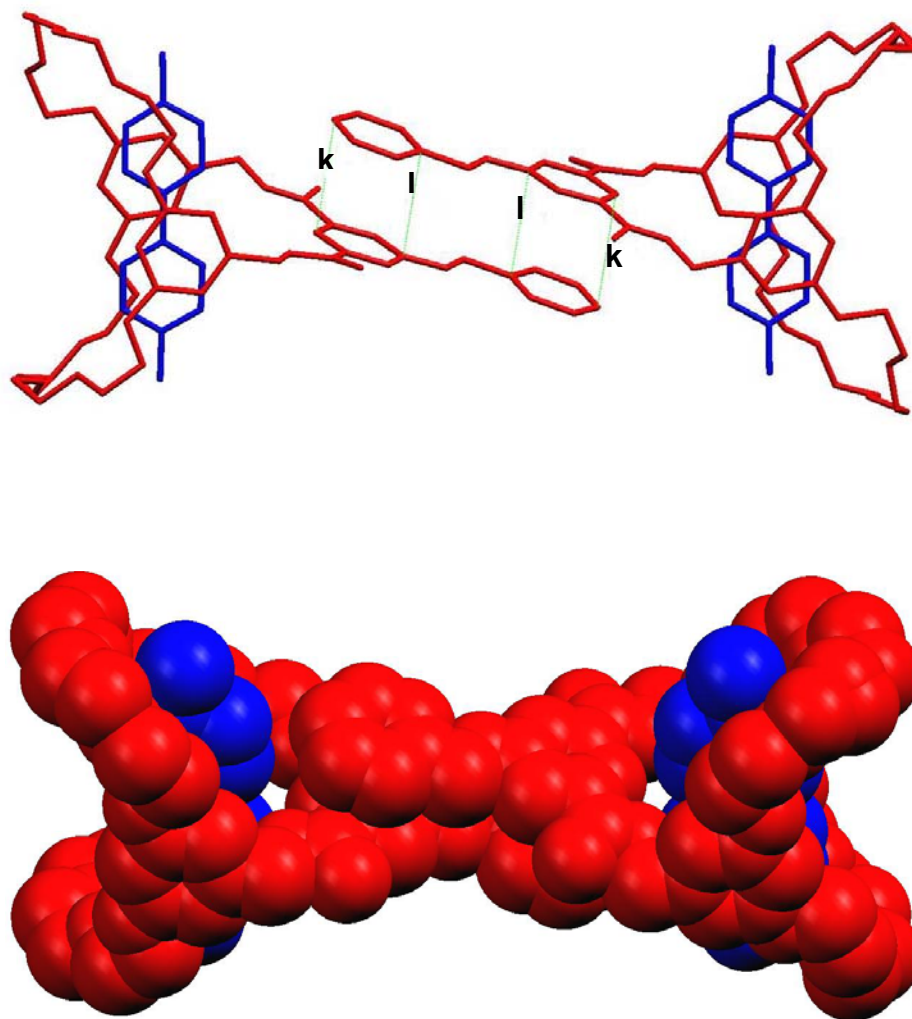


Figure 4. Two views of the dimer structure $(\mathbf{1}\cdot\mathbf{3})_2$. $\mathbf{1}$ molecules are red and $\mathbf{3}$ molecules are blue. Solvent molecules, four PF_6 counterions, and hydrogens have been omitted for clarity. Face-to-face π -stacking parameters: centroid-centroid distances (\AA) 3.60, 3.60; ring plane/ring plane inclinations (deg): 3.8, 3.8; \mathbf{k} = 3.61 \AA ; \mathbf{l} = 3.62 \AA .

11.3. CONCLUSIONS

In summary, two new dimers of inclusion complexes were successfully prepared as shown by electrospray ionization mass spectrometry and X-ray analysis. Future work will be to apply **1** in the construction of other supramolecular systems.

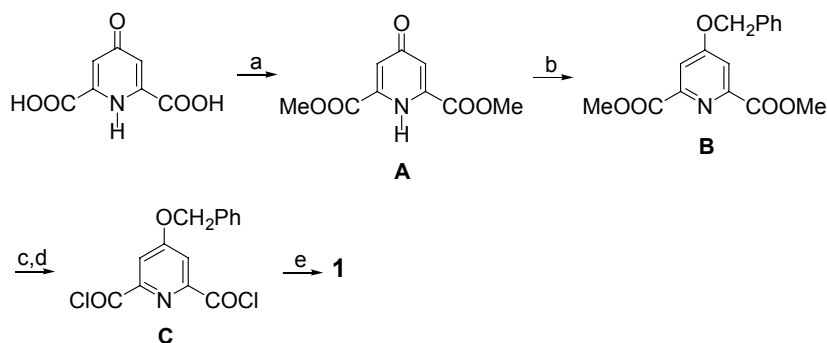
11.4. ACKNOWLEDGEMENTS

We acknowledge the National Science Foundation (NSF) for the financial support of this research through DMR0097126 (HWG) and the Environmental Management Science Program, Office of Science, U.S. Department of Energy for a fellowship (JWJ) via the Higher Education Research Experience (HERE) at Oak Ridge National Laboratory. We also thank NSF (CHE-0131128) for funding of the purchase of the Oxford Diffraction Xcalibur2 single crystal diffractometer.

11.5. SUPPORTING INFORMATION

Synthesis of **1**

Scheme S1. Synthesis of **1**.*



* Reagents and conditions: (a) CH₃OH, H₂SO₄, reflux; (b) benzyl chloride, K₂CO₃, DMF, 90 °C; (c) KOH, ethyl ether, HCl, RT; (d) C₆H₆, SOCl₂, DMF, reflux; (e) **2**, triethylamine, CH₂Cl₂, RT.

A,^{S1} **B**,^{S2} **C**,^{S3} and **2**^{S4} were prepared by using the methods described in the literature. Other reagents were used as received.

Synthesis of 1. A solution of 0.70 g (1.2 mmol) **2** and 0.50 mL triethylamine in 45 mL dichloromethane and a solution of 0.37 g (1.2 mmol) **C** in 45.5 mL dichloromethane were added dropwise at the same rate (0.69 mL/h) to 1400 mL dichloromethane in a flask equipped with a magnetic stirrer at RT under nitrogen gas protection. The reaction mixture was stirred for 4 hours after the complete addition of reactants. The solvents were removed to afford a viscous yellow oil. The oil then was dissolved in 50 mL chloroform and washed with water (3 × 50 mL) and 5% sodium bicarbonate (3 × 50 mL). After the removal of solvents, the crude product was purified by flash column chromatography, eluting with dichloromethane:methanol (25:1) to give 0.21 g **1** (21%): mp 129-131 °C. ¹H NMR (400 MHz, CDCl₃, 22 °C) δ 7.94 (s, 2H), 7.36-7.50 (m, 5H), 6.54 (d, *J* = 2.4 Hz, 4H), 6.46 (t, *J* = 2.4 Hz, 2H), 5.30 (s, 2H), 5.25 (s, 4H), 3.95 (t, *J* = 4.0 Hz, 8H), 3.77 (t, *J* = 4.0 Hz, 8H), 3.62-3.70 (m, 16H). Anal. calcd for C₄₄H₅₁NO₁₅: C, 63.38; H, 6.16; N, 1.68. Found: C, 63.54; H, 6.22; N, 1.66. LRFABMS (matrix, NBA) *m/z* 856 [M + Na]⁺, 834 [M + H]⁺; HRFABMS (matrix, NBA/PEG) *m/z* calcd for [M + H]⁺ C₄₄H₅₂NO₁₅, 834.33370, found 834.33405, error 0.4 ppm.

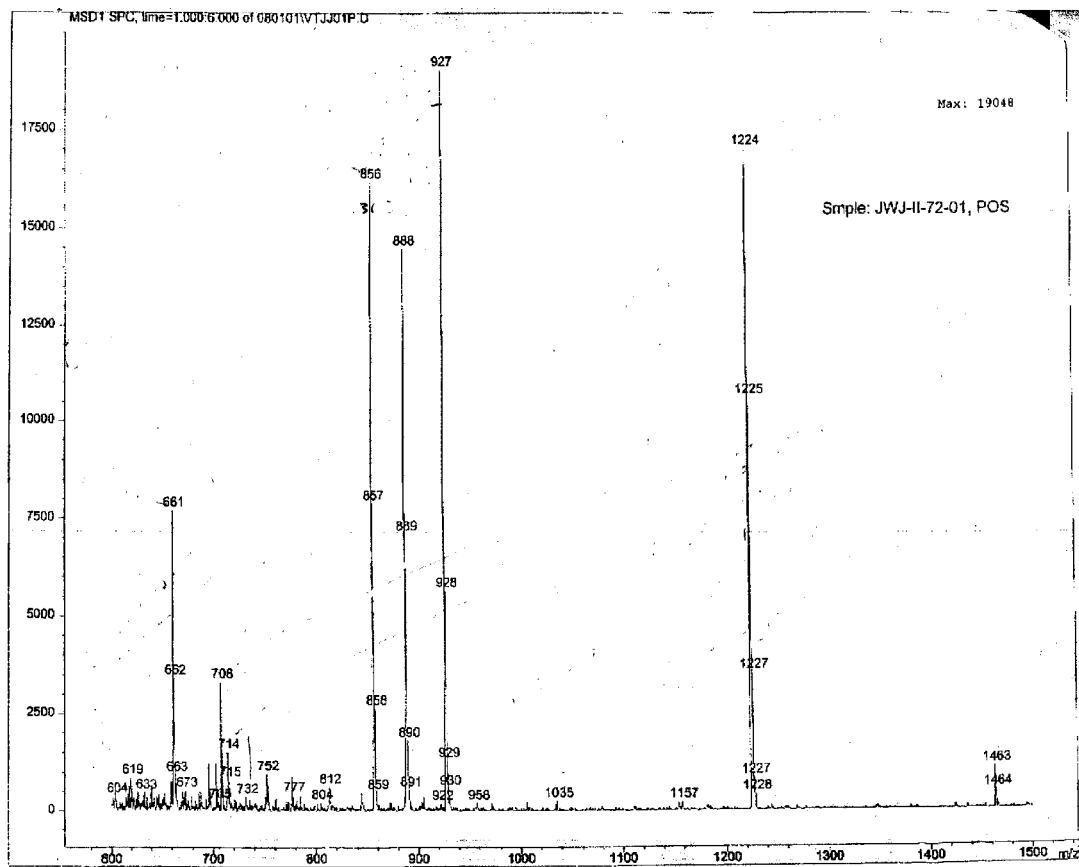
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Electrospray mass spectrum of a solution of 1 and 6 in acetone



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Crystal data: prism, yellow, $0.39 \times 0.25 \times 0.14 \text{ mm}^3$, $\text{C}_{59}\text{H}_{67}\text{F}_{12}\text{N}_3\text{O}_{18}\text{P}_2$, FW 1396.11, triclinic, space group $P-1$, $a = 13.2363(15)$, $b = 16.1803(16)$, $c = 16.5673(15) \text{ \AA}$; $\alpha = 102.397(8)^\circ$, $\beta = 93.336(8)^\circ$, $\gamma = 110.76(1)^\circ$; $V = 3205.1(6) \text{ \AA}^3$, $Z = 2$, $D_c = 1.447 \text{ g cm}^{-3}$, $T = 100 \text{ K}$, $\mu = 1.75 \text{ cm}^{-1}$, 35061 measured reflections, 16428 independent reflections [$R(\text{int}) = 0.06$], 865 parameters, $F(000) = 1448$, $R_1 = 0.1335$, $wR_2 = 0.1243$ (all data), $R_1 = 0.0946$, $wR_2 = 0.1197$ [$I > 1\sigma(I)$], and $\text{GooF} (F^2) = 1.0343$. Nonhydrogen atoms were treated anisotropically and hydrogen atoms were placed in calculated positions. 10613 reflections were used in refinements by full-matrix least-squares on F^2 . The structure was solved by direct methods using SIR¹³ and refined by full-matrix least squares, using the Crystals.¹⁴ CCDC-220318. See <http://www.rsc.org/suppdata/cc/...> for a CIF file of this structure.

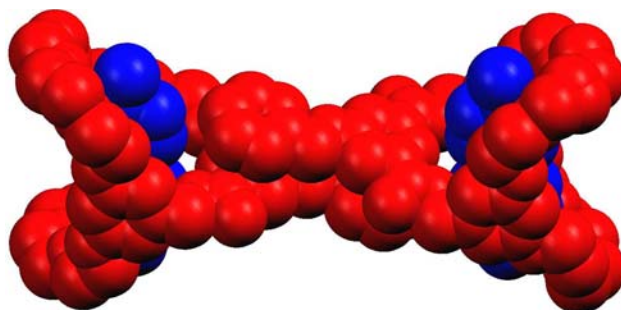
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TOC Graphic:



Abstract: Dimers are formed from inclusion complexes of a new cryptand with paraquats, driven by dipole-dipole and face-to-face π -stacking interactions as shown by electrospray mass spectrometric characterization and X-ray analysis.
