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Efficient syntheses of bis(*m*-phenylene)-26-crown-8-based cryptand/paraquat derivative [2]rotaxanes by immediate solvent evaporation method

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ABSTRACT

A novel bis(*m*-phenylene)-26-crown-8-based cryptand has been synthesized. It has been used to prepare two 1:1 complexes with two paraquat derivatives with high association constants (6.5×10^5 and 4.0×10^5 M^{-1}) in acetone. In the solid state the cryptand forms a 2:1 threaded structure with paraquat and an interesting supramolecular poly[2]pseudorotaxane threaded structure with a dihydroxyethyl-substituted paraquat derivative, respectively. It has been further used to prepare cryptand/paraquat derivative [2]rotaxanes efficiently by the immediate solvent evaporation method using easily available 3,5-dimethylphenyl groups as the stoppers.

1. Introduction

Non-covalent interactions are universal and important in biological systems, which motivated chemists to take advantage of them to elegantly prepare complicated supramolecular architectures,[1] including interlocked threaded structures[2] and supramolecular polymers.[3] These supramolecular architectures have been widely used in nanoscience and nanotechnology.[4]

Paraquat derivatives (*N*,*N*′-dialkyl-4,4′-bipyridinium salts) have been widely used to prepare threaded structures with crown ether,[5] bicyclic (cryptand),[6] and tricyclic hosts.[3c,7] Usually pseudorotaxanes are intermediates to prepare interlocked threaded structures, thus higher stabilities or association constants of pseudorotaxanes will lead to higher yields in the fabrication of interlocked threaded structures. It has been proved that crown ether-based cryptands can form pseudorotaxanes with paraquat derivatives and bind them much more strongly than the corresponding simple crown ethers.[6] However, so far mechanically interlocked structures based on the cryptand/paraquat derivative recognition motif are still rare. Only examples are two [2]rotaxanes, for which bis(*m*-phenylene)-32-crown-10-based cryptands served as the macrocycles, recently reported by us.[8] Considering that the efficient fabrication of mechanically interlocked structures is necessary for their future applications in nanoscience and nanotechnology and to further explore the cryptand/paraquat derivative recognition motif in the preparation of mechanically interlocked structures, we prepared a novel bis(*m*-phenylene)-26-crown-8-based cryptand **1**, studied its complexations with paraquat derivatives **2** and **3**, and further used it in the efficient syntheses of cryptand/paraquat derivative [2]rotaxanes using easily available 3,5-dimethylphenyl groups as the stoppers. Moreover, here the immediate solvent evaporation method (ISEM)[9] was adopted to prepare the [2]rotaxanes, considering that ISEM can significantly accelerate organic reactions compared to the conventional solution conditions without any decrease in the yield. The results of these studies are reported here.

2. Results and discussion

2.1. Synthesis of bis(*m*-phenylene)-26-crown-8-based 2,6-pyridino-cryptand 1

The diester **4**,[10] prepared from the cyclization reaction between methyl 3,5-bis(2-(2-(2-chloroethoxy)ethoxy)ethoxy)benzoate and methyl 3,5-dihydroxybenzoate, was reduced with $LiAlH_4$ to the corresponding bis(*m*-phenylene)-26-crown-8 diol **5**, which further reacted with pyridine-2,6-dicarbonyl chloride using the pseudo-high dilution technique[11] to afford bis(*m*-phenylene)-

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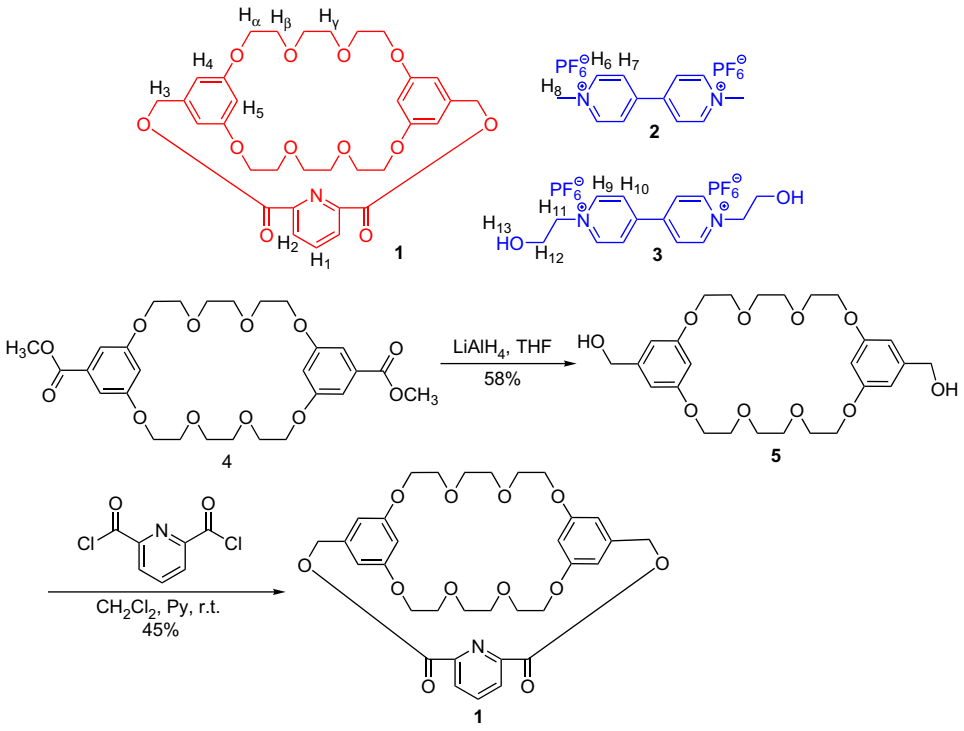


Scheme 1. Synthesis of bis(*m*-phenylene)-26-crown-8-based 2,6-pyridino-cryptand **1** from bis(*m*-phenylene)-26-crown-8 diester **4**.

26-crown-8-based 2,6-pyridino-cryptand **1** in 45% yield, as shown in Scheme 1. The host **1** was characterized by ^{1}H NMR, ^{13}C NMR, and HRESIMS.

2.2. The determination of stoichiometries of the complexations between host 1 and either of guests 2 and 3

Then the complexations between **1** and either of **2** and **3** were studied. When equimolar (2.00 mM) acetone solutions of cryptand **1** and either of paraquat derivative salts **2** and **3** were made, a bright yellow color appeared as a result of charge-transfer interactions between electron-rich aromatic rings of the cryptand host and electron-poor pyridinium rings of the paraquat derivative guest. Job plots[12] (Fig. 1) based on UV–vis absorption spectroscopy data of the charge-transfer band (λ=370 nm) proved that the complexes of **1** with **2** or **3** were of 1:1 stoichiometry in solution.

2.3. Determination of association constants of 1·2 and 1·3

Then association constants (K_a) of complexes **1**·**2** and **1**·**3** were determined by probing the charge-transfer band of the complexes by UV–vis spectroscopy and employing a titration method. Progressive addition of an acetone solution with high guest **2** or **3** concentration and low host **1** concentration to an acetone solution with the same host **1** concentration resulted in an increase of the intensity of the charge-transfer band of the complex. Treatment of the collected absorbance data at λ=370 nm with a non-linear curve-fitting program afforded the corresponding K_a values: 6.5 ($\pm$1.8)$\times10^5$ M^{-1} for **1**·**2** and 4.0 ($\pm$0.7)$\times10^5$ M^{-1} for **1**·**3**.[13] Comparison of the K_a value of **1**·**2** with previously reported K_a values of complexes based on analogous bis(*m*-phenylene)-32-crown-10- and dibenzo-24-crown-8-based pyridyl ester cryptands with paraquat **2** indicated that the bis(*m*-phenylene)-32-crown-10-based cryptand (K_a=5.0$\times10^6$ M^{-1} in acetone)[6d] is better for **2** than the bis(*m*-phenylene)-26-crown-8-based cryptand (K_a=6.5$\times10^5$ M^{-1} in acetone) while the bis(*m*-phenylene)-26-crown-8-based cryptand is better than the dibenzo-24-crown-8-based cryptand (K_a=1.2$\times10^5$ M^{-1} in acetone).[6f] In view of the fact that all these three cryptands have the same third chain, the large difference in K_a values could probably be attributed to the more aliphatic ethyleneoxy oxygen atoms, efficient hydrogen bond acceptors, that the bis(*m*-phenylene)-32-crown-10-based cryptand has than the other two cryptand analogs. The reason for us to use a bis(*m*-phenylene)-26-crown-8-based cryptand instead of a bis(*m*-phenylene)-32-crown-10-based cryptand as the macrocycle to make [2]rotaxanes here is that the cavity of the bis(*m*-phenylene)-26-crown-8-based cryptand is smaller than that of the corresponding bis(*m*-phenylene)-32-crown-10-based cryptand and appropriate stoppers are more easily available.

2.4. The ^{1}H NMR study of the complexation of host 1 with either of guests 2 and 3

To further investigate the complexations between **1** and either of **2** and **3**, proton NMR spectra of equimolar (4.00 mM) acetone-d_6 solutions of **1** with either of **2** and **3** were examined (Fig. 2). Both of the two complexation systems **1**·**2** and **1**·**3** are fast exchange on the proton NMR time scale. The chemical shift changes of protons on cryptand host **1** showed some similar characteristics after complexation with **2** and **3**. Significant upfield shifts were observed for aromatic protons H_4 and H_5. Pyridyl protons H_1 and H_2, β-ethyleneoxy protons H_β, and γ-ethyleneoxy protons H_γ had downfield shifts while benzyl protons H_3 and α-ethyleneoxy protons H_α moved upfield. Pyridinium protons H_6, H_7, H_9, and H_{10} of **2** and **3** and methyl protons H_8 of **2** moved upfield while methylene protons H_{12} and hydroxyl protons H_{13} of **3** moved downfield after complexation of **1** with **2** and **3**. *N*-Methylene protons H_{11} of **3** did not have an obvious chemical shift change. Moreover, the appearance of broad signals for the complexation system **1**·**3** in the ^{1}H NMR

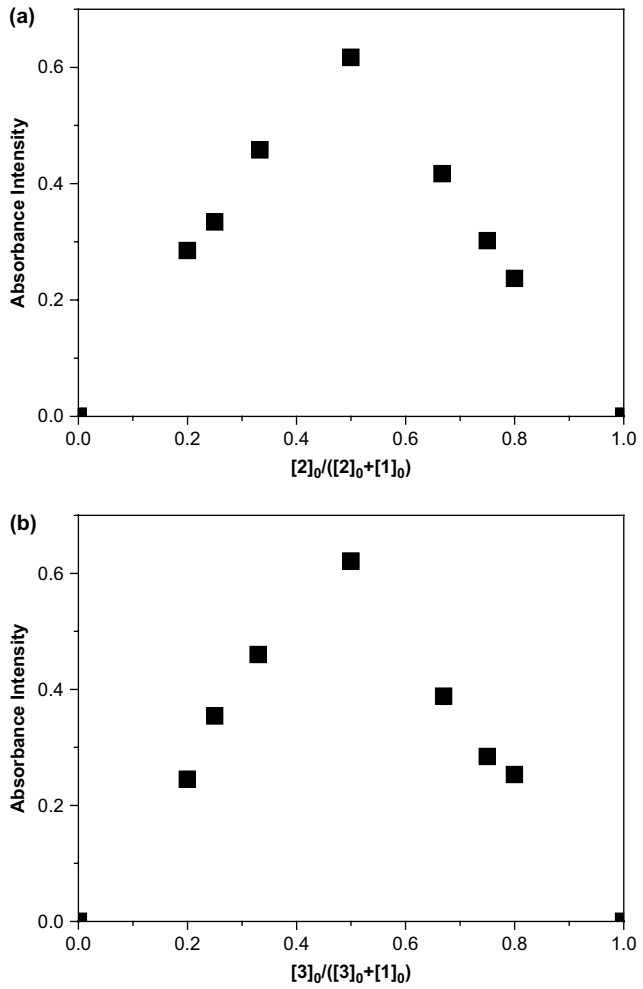


Figure 1. Job plots showing the 1:1 stoichiometries of the complexes between **1** and **2** (a) and **1** and **3** (b) in acetone by plotting the absorbance intensity at λ=370 nm (the host–guest charge-transfer band) against the mole fraction of the guest. $[\mathbf{1}]_0$, $[\mathbf{2}]_0$, and $[\mathbf{3}]_0$ are initial concentrations of **1**, **2**, and **3**. $[\mathbf{1}]_0+[\mathbf{2}]_0=[\mathbf{1}]_0+[\mathbf{3}]_0=1.00$ mM.

spectrum (Fig. 2d) suggested that the exchange rates during the complexation and decomplexation processes were slow on the ^{1}H NMR spectroscopic time scale, which could result from the relatively longer β-hydroxyethyl substitution groups of compound **3**, compared with the methyl substitution groups of compound **2**.[6f]

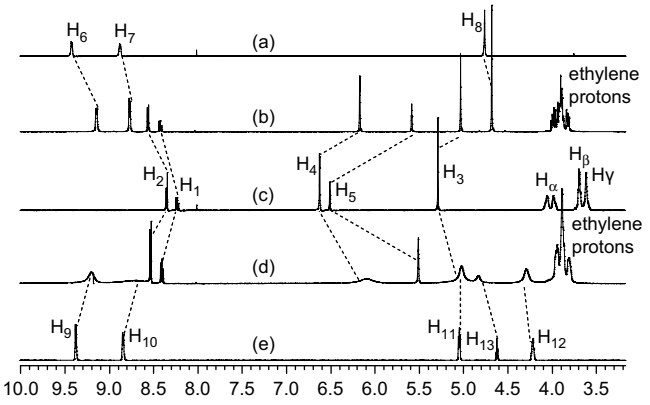


Figure 2. Partial ^{1}H NMR spectra (500 MHz, acetone-d_6, 295 K) of (a) paraquat **2**, (b) 4.00 mM cryptand **1** and **2**, (c) cryptand **1**, (d) 4.00 mM cryptand **1** and **3**, and (e) paraquat derivative **3**.

2.5. Electrospray ionization mass spectrometry

The electrospray ionization mass spectrometry characterization was done on solutions of **1** with either of **2** and **3**. Peaks were found at *m*/*z* 970.0 (100%) and 1030.1 (100%) for complexes **1**·**2** and **1**·**3**, respectively, corresponding to $[\mathbf{1}\cdot\mathbf{2}-PF_6]^+$ and $[\mathbf{1}\cdot\mathbf{3}-PF_6]^+$. Moreover, a peak was found at *m*/*z* 732.5 (59%) corresponding to 2:1 complex **1**·**2**·**1**. However, no peaks corresponding to other stoichiometries were found in complexations of **1** with either of **2** and **3**.

2.6. Crystal structures of complexes 1·2 and 1·3

Single crystals suitable for X-ray crystallography were obtained by vapor diffusion of diisopropyl ether into solutions of **1** with either of **2** and **3** in CH_3CN. Cryptand **1** and paraquat **2** formed a 2:1 complex in the solid state (Fig. 3), which is not consistent with their 1:1 complexation stoichiometry in solution. The 2:1 complex **1**·**2**·**1**, a pseudorotaxane-like [3]complex, is stabilized by hydrogen bonding and face-to-face π-stacking interactions between the aromatic rings of **1** and the pyridinium rings of **2**. Previously it was reported that a different bis(*m*-phenylene)-26-crown-8-based cryptand with a tri(ethylene glycol) third chain can also form a 2:1 complex with **2** in the solid state as confirmed by single crystal X-ray analysis.[6c] Similar to that complex, here none of *N*-methyl hydrogens of **2** are involved in hydrogen bonding between the host and guest in **1**·**2**·**1** either, and four β-pyridinium hydrogens of **2** form four hydrogen bonds (**d** and **g** in Fig. 3) with four ethyleneoxy oxygen atoms of the host too. Here the two cryptand host molecules of **1**·**2**·**1** are also connected by two hydrogen bonds (**h** in Fig. 3). However, there are some differences due to the structure difference of the two cryptand hosts. In the previous complex four α-pyridinium hydrogens of **2** form six hydrogen bonds directly with the ethyleneoxy oxygen atoms of the cryptand host.[6c] In **1**·**2**·**1** two water molecules serve as hydrogen bonding bridges and two α-pyridinium hydrogens of **2** are indirectly connected to the host by six hydrogen bonds (**a**, **b**, and **c** in Fig. 3) while the other two

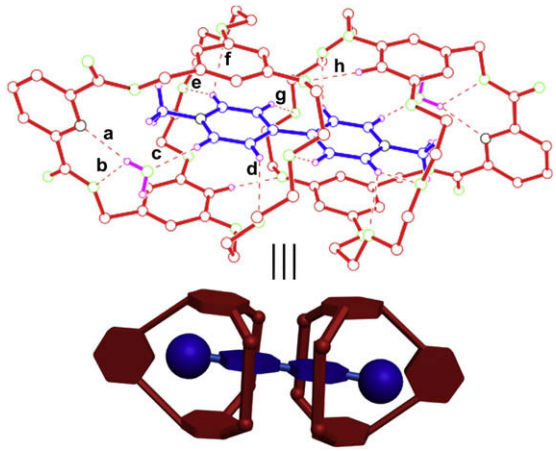


Figure 3. A ball-stick view of the X-ray structure of **1**·**2**·**1**. **1** is red, **2** is blue and water molecules are magenta. Hydrogens are magenta, oxygens are green, and nitrogens are black. PF_6^- counterions, other solvent molecules and hydrogens except the ones on **2** or involved in hydrogen bonding were omitted for clarity. Hydrogen bond parameters: H···O (N) distance (Å), C(O)–H···O (N) angle (deg), C(O)···O (N) distance (Å) **a**, 2.12, 156, 3.16; **b**, 2.53, 135, 3.32; **c**, 2.42, 173, 3.37; **d**, 2.51, 143, 3.32; **e**, 2.48, 158, 3.38; **f**, 2.43, 132, 3.14; **g**, 2.64, 150, 3.49; **h**, 2.32, 173, 3.27. Face-to-face π-stacking parameters: centroid–centroid distances (Å) 3.42, 3.94; ring plane/ring plane inclinations (deg): 0.7, 7.4. The centroid–centroid distance (Å) and dihedral angle (deg) between the two pyridinium rings of **2**: 4.29, 0.3.

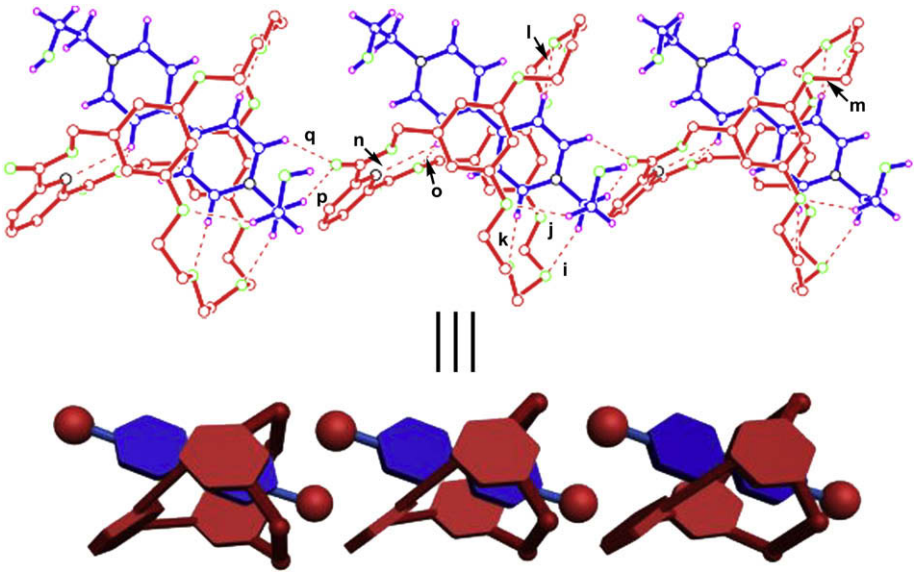


Figure 4. A ball-stick view of the X-ray packing structure of **1**·**3**. **1** is red, **3** is blue, hydrogens are magenta, oxygens are green, and nitrogens are black. PF_6^- counterions, solvent molecules and hydrogens except the ones on **3** were omitted and only three [2]pseudorotaxanes are shown here for clarity. Hydrogen bond parameters: H···O (N) distance (Å), C–H···O (N) angle (deg), C···O (N) distance (Å) **i**, 2.60, 150, 3.50; **j**, 2.38, 162, 3.35; **k**, 2.42, 152, 3.34; **l**, 2.35, 134, 3.13; **m**, 2.56, 159, 3.52; **n**, 2.70, 125, 3.37; **o**, 2.47, 122, 3.13; **p**, 2.35, 148, 3.24; **q**, 2.46, 124, 3.13. Face-to-face π-stacking parameters: centroid–centroid distances (Å) 3.62, 3.77; ring plane/ring plane inclinations (deg): 11.1, 1.6. The centroid–centroid distance (Å) and dihedral angle (deg) between the two pyridinium rings of **3**: 4.28, 19.0.

α-pyridinium hydrogens are directly connected to the host by four hydrogen bonds (**e** and **f** in Fig. 3).

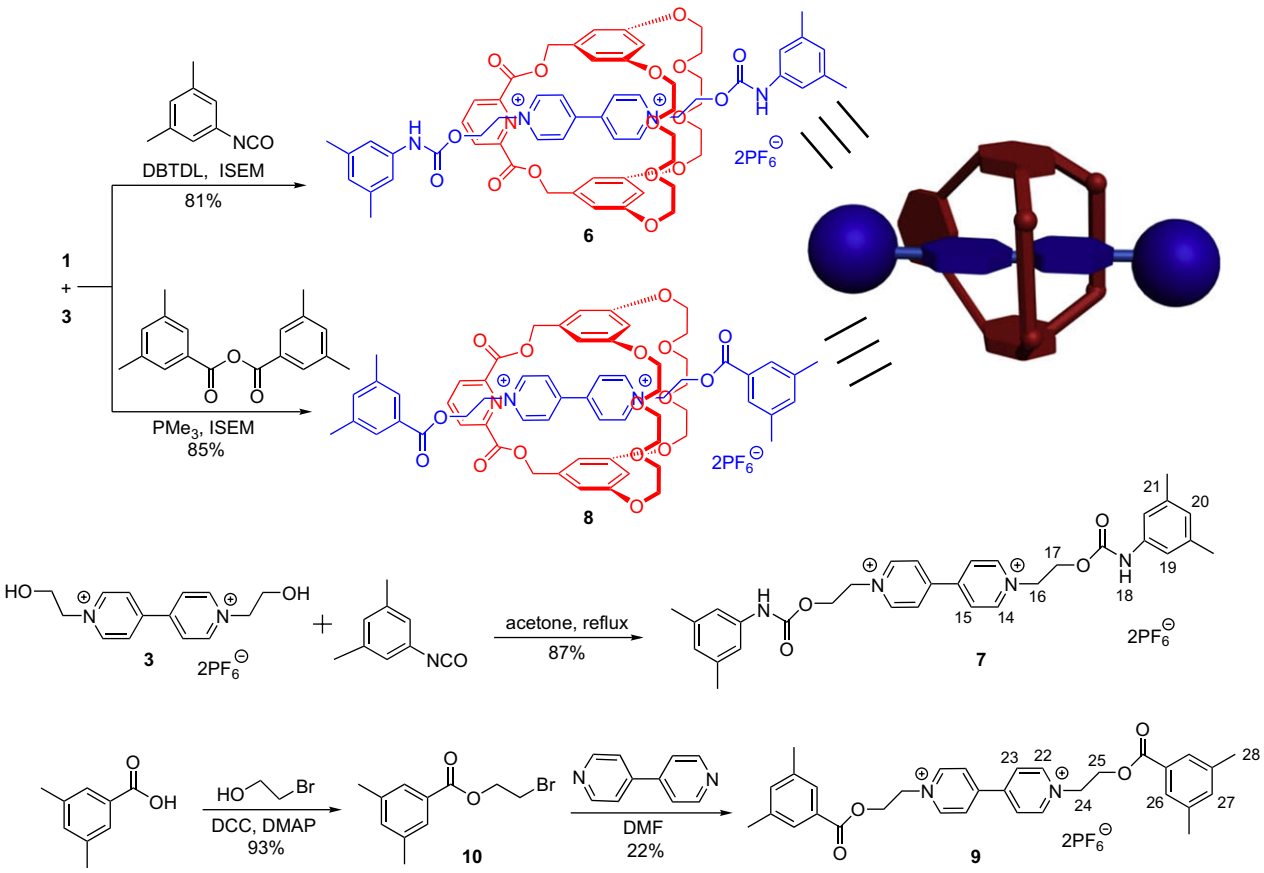
The crystal structure of **1**·**3** (Fig. 4) revealed its expected [2]pseudorotaxane binding geometry. Just like **1**·**2**·**1**, **1**·**3** is also stabilized by hydrogen bonding and face-to-face π-stacking interactions in the solid state (Fig. 4). In the previously reported crystal structure of a complex of **3** with a dibenzo-24-crown-8-based pyridyl ester cryptand,[6f] paraquat derivative guest **3** is symmetrically threaded into the cavity of the cryptand host and none of its eight ethylene hydrogens are involved in hydrogen bonding between the host and guest while here **3** is threaded unsymmetrically into the cavity of bis(*m*-phenylene)-26-crown-8-based cryptand host **1** and two of its eight ethylene hydrogens are involved in hydrogen bonding (**i** and **j** in Fig. 4) between the host and guest. In the above crystal structure of **1**·**2**·**1** all eight pyridinium hydrogens are involved in hydrogen bonding between the host and guest (Fig. 4), here only one α-pyridinium and two β-pyridinium hydrogens are involved in hydrogen bonding (**k**, **l**, **m**, **n**, and **o** in Fig. 4) between the host and guest. Only one of the two pyridinium rings of **3** is involved in face-to-face π-stacking interactions with the two phenylene rings of **1** (Fig. 4). The dihedral angle between the two pyridinium rings of **3** is 19.0° (Fig. 4). This twist presumably results from the maximization of hydrogen bonding interactions between **1** and **3** as well as minimization of the steric repulsion between the adjacent hydrogens on **3**. Interestingly, an ester carbonyl oxygen atom of cryptand host **1** forms two hydrogen bonds (**p** and **q** in Fig. 4) with one α-pyridinium hydrogen and one *N*-ethylene hydrogen of the paraquat derivative guest **3** in the neighboring [2]pseudorotaxane and [2]pseudorotaxanes are arranged linearly to form a supramolecualr poly[2]pseudorotaxane threaded structure (Fig. 4).

2.7. Preparation of [2]rotaxanes by ISEM

Considering ISEM can accelerate organic reactions significantly because the remarkable enhancement of molecule-to-molecule contacts between reactants,[9] here we used it to prepare two cryptand/paraquat derivative [2]rotaxanes based on acylation reactions (the urethane formation as well as the esterification reactions) (Scheme 2).

Mixing **1** (0.019 mmol), **3** (0.017 mmol), 3,5-dimethylphenyl isocyanate (0.102 mmol), and catalytic amount of dibutyltin dilaurate (DBTDL) in anhydrous acetonitrile (0.4 mL) followed by evaporation afforded a film, which further stood for 2 h at ambient temperature. It was observed on the TLC plate that compound **3** was completely converted while only a slight amount of dumbbell compound **7** was formed. Purification by flash column chromatography afforded [2]rotaxane **6** in 81% yield. By contrast, the reaction proceeding in the solution was also conducted using threading-followed-by-stoppering method. Stirring the reaction mixture at room temperature for 2 days followed by column chromatography afforded [2]rotaxane **6** in 83% yield. It clearly showed that reaction was accelerated by ISEM. Moreover, when using 3,5-dimethylbenzoic anhydride as the stopper and catalytic amount of trimethylphosphine as the base, [2]rotaxane **8** was prepared in 85% yield with ISEM (Scheme 2). Hence, cryptand/paraquat derivative rotaxanes could be efficiently prepared with ISEM due to the strong binding between **1** and **3**.

Partial proton NMR spectra of dumbbell-shaped components **7** and **9**, [2]rotaxanes **6** and **8** as well as the cryptand **1** in acetone-d_6 are shown in Figure 5. Chemical shift changes were found for all protons of **1** and dumbbell-shaped compounds after the formation of rotaxanes (Fig. 5). These chemical shift changes persisted even in DMSO (Figs. S27 and S28), proving that **6** and **8** are rotaxanes since no complexation is expected in this highly polar solvent.[14] Furthermore, protons of **7** and **9** were all split into two sets (Fig. 5), further confirming that the threading of paraquat derivatives into the cavity of cryptand **1** is unsymmetrical. The successful preparation of rotaxanes **6** and **8** proved that easily accessible 3,5-dimethylphenyl group is big enough to serve as stoppers for rotaxanes with cryptand **1** as the macrocycle and acylation reactions are applicable stoppering methods for preparing rotaxanes by ISEM.



Scheme 2. Synthesis of two bis(*m*-phenylene)-26-crown-8-based cryptand/paraquat derivative [2]rotaxanes and their corresponding dumbbell-shaped compounds.

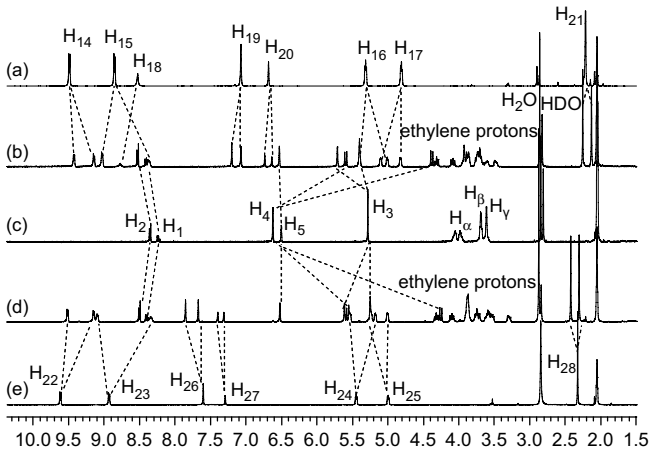


Figure 5. Partial ^{1}H NMR spectra (400 MHz, acetone-d_6, 295 K) of (a) dumbbell component **7**, (b) rotaxane **6**, (c) cryptand **1**, (d) rotaxane **8**, (e) dumbbell component **9**.

3. Conclusion

In summary, we have reported here that the novel bis(*m*-phenylene)-26-crown-8-based cryptand **1** is a highly efficient host for the complexation of paraquat derivatives. Consequently, this cryptand was used to efficiently prepare cryptand/paraquat derivative [2]rotaxanes by ISEM, for which easily available 3,5-dimethylphenyl groups served as the stoppers and acylation reactions are applicable methods. ISEM could accelerate the reaction of preparing [2]rotaxanes obviously. The present results may stimulate further studies on cryptand/paraquat derivative functional threaded structures.

4. Experimental section

4.1. General

Methyl 3,5-dihydroxybenzoate and tri(ethylene glycol)dichloride were reagent grade and used as received. Solvents were either employed as purchased or dried according to procedures described in the literature. NMR spectra were recorded on a Bruker Advance DMX 500 spectrophotometer or a Bruker Advance DMX 400 spectrophotometer using the deuterated solvent as the lock and the residual solvent or TMS as the internal reference. Low-resolution electrospray ionization mass spectra were recorded on a Bruker Esruire 3000 Plus spectrometer. High-resolution mass spectrometry experiments were performed on a Bruker Daltonics Apex III spectrometer.

4.2. Bis(*m*-phenylene)-26-crown-8-based 2,6-pyridinocryptand (1)

Pyridine (0.20 mL) was added to the solution of $SOCl_2$ (7.50 mL, 100 mmol) and pyridine-2,6-dicarboxylic acid (3.34 g, 20 mmol). The mixture was stirred at room temperature for 10 h. The solvent was removed with a rotary evaporator to afford pyridine-2,6-dicarbonyl dichloride as a white solid (2.98 g), which was collected for the next step without further purification. To a solution of bis(5-hydroxymethyl-*m*-phenylene)-26-crown-8 **5** (1.00 g, 1.97 mmol) in dichloromethane (800 mL) at 0 °C under an atmosphere of nitrogen

was added pyridine (0.32 g, 4.00 mmol). A solution of 2,6-pyridinedicarbonyl dichloride (0.42 g, 2.07 mmol) in dichloromethane (20 mL) was slowly added dropwise over 3 h while keeping the solution at 0 °C. The solution was then allowed to warm to room temperature and stirred for 7 days before being concentrated in vacuo. The resulting mixture was dissolved in chloroform (60 mL) and washed with 2 M HCl and brine. The organic layer was evaporated to dryness using a rotary evaporator producing a yellow oil residue. Purification of the residue by flash column chromatography (dichloromethane/ethyl acetate, 6:1 v/v) afforded **1** as a white solid (0.57 g, 45%). Mp 174–176 °C. ^{1}H NMR (400 MHz, acetone-d_6, room temperature) δ (ppm): 8.30 (d, J=8.0 Hz, 2H), 8.18 (t, J=8.0 Hz, 1H), 6.57 (s, 4H), 6.45 (s, 2H), 5.23 (s, 4H), 4.00 (s, 4H), 3.93 (s, 4H), 3.65 (br s, 8H), 3.56 (s, 8H). ^{13}C NMR (125 MHz, acetone-d_6/chloroform-d (1/1, v/v), room temperature) δ (ppm): 165.1, 160.1, 148.3, 138.5, 136.7, 128.4, 107.1, 102.3, 71.2, 69.9, 68.2, 67.4. HRESIMS: m/z calcd for $[M+H]^+$ $C_{33}H_{38}NO_{12}$, 640.2394, found 640.2396, error 0.3 ppm.

4.3. Rotaxane 6

4.3.1. By the immediate solvent evaporation method

A mixture of bis(*m*-phenylene)-26-crown-8-based cryptand **1** (12.0 mg, 0.019 mmol), paraquat diol **3** (9.2 mg, 0.017 mmol), 3,5-dimethylphenyl isocyanate (15.0 mg, 0.102 mmol), and catalytic amount of dibutyltin dilaurate (DBTDL, 1.5 mg) was dissolved in acetonitrile (0.4 mL). The resulting yellow solution was evaporated in vacuo, whereupon a film developed on the surface of the flask. After 5 min, the evaporation was stopped and the film was left standing in the open air at ambient temperature for 2 h. The mixture was dissolved in acetonitrile and H_2O. A saturated aqueous solution of NH_4PF_6 was added to the reaction mixture. On removal of acetonitrile, a yellow precipitate was formed, which was filtered off and dried in vacuo to afford the crude product, which was purified by flash column chromatography (CH_2Cl_2/MeOH/CH_3NO_2, 30:1:1 v/v/v) to yield rotaxane **6** as a yellow film (20.3 mg, 81%).

4.3.2. By the reaction in solution

A mixture of bis(*m*-phenylene)-26-crown-8-based cryptand **1** (12.0 mg, 0.019 mmol), paraquat diol **3** (9.2 mg, 0.017 mmol), 3,5-dimethylphenyl isocyanate (15.0 mg, 0.102 mmol), and catalytic amount of dibutyltin dilaurate (DBTDL, 1.5 mg) was dissolved in anhydrous acetonitrile (5.0 mL). The mixture was stirred at room temperature for 2 days. Then it was dissolved in acetonitrile and H_2O. A saturated aqueous solution of NH_4PF_6 was added to the reaction mixture. On removal of acetonitrile, a yellow precipitate was formed, which was filtered off and dried in vacuo to afford the crude product, which was purified by flash column chromatography (CH_2Cl_2/MeOH/CH_3NO_2, 30:1:1 v/v/v) to yield **6** as a yellow film (20.7 mg, 83%). ^{1}H NMR (400 MHz, acetone-d_6, room temperature) δ (ppm): 9.37 (d, J=6.4 Hz, 2H), 9.08 (d, J=6.4 Hz, 2H), 8.97 (d, J=6.4 Hz, 2H), 8.72 (br, 2H), 8.47 (d, J=8.0 Hz, 2H), 8.35 (d, J=8.0 Hz, 1H), 8.32 (d, J=6.4 Hz, 2H), 7.14 (s, 2H), 7.02 (s, 2H), 6.68 (s, 1H), 6.58 (s, 1H), 6.47 (s, 2H), 5.66 (s, 2H), 5.54 (d, J=11.6 Hz, 2H), 5.35 (br s, 4H), 5.05 (br s, 2H), 4.95 (br s, 2H), 4.77 (br s, 2H), 4.33 (d, J=11.6 Hz, 2H), 3.41–4.28 (m, 24H), 2.20 (s, 6H), 2.08 (s, 6H). ^{1}H NMR (400 MHz, DMSO-d_6, room temperature) δ (ppm): 9.85 (br s, 1H), 9.67 (br s, 1H), 9.25 (d, J=6.4 Hz, 2H), 8.78 (d, J=6.4 Hz, 2H), 8.72 (d, J=6.4 Hz, 2H), 8.51 (d, J=8.0 Hz, 2H), 8.38 (t, J=8.0 Hz, 1H), 7.10 (s, 2H), 6.95 (s, 2H), 6.67 (s, 1H), 6.58 (s, 1H), 6.38 (s, 2H), 5.52 (s, 2H), 5.43 (d, J=11.6 Hz, 2H), 5.27 (s, 2H), 5.22 (br s, 2H), 4.95 (br s, 2H), 4.82 (br s, 2H), 4.66 (br s, 2H), 4.24 (d, J=11.6 Hz, 2H), 3.40–4.21 (m, 24H), 2.21 (s, 6H), 2.08 (s, 6H). ^{13}C NMR (125 MHz, acetone-d_6, room temperature) δ (ppm): 164.9, 160.0, 158.4, 152.9, 148.8, 147.4, 146.0, 145.5, 145.2, 139.4, 138.6, 138.5, 138.4, 138.1, 137.2, 129.1, 125.9, 125.0, 124.8, 116.8, 116.2, 110.1, 104.6, 101.2, 70.8, 70.5, 69.9, 69.8, 67.4, 67.3, 67.1, 63.2, 63.1, 61.5, 60.1, 20.6, 20.5. HRESIMS: m/z calcd for $[M-PF_6]^+$ $C_{65}H_{73}F_6N_5O_{16}P$, 1324.4694, found 1324.4639, error 4.2 ppm.

4.4. Dumbbell-shaped component 7

Paraquat diol **3** (0.268 g, 0.50 mmol) and 3,5-dimethylphenyl isocyanate (0.176 g, 1.20 mmol) were dissolved in acetone (15 mL) and heated at reflux for 20 h. It was then cooled to room temperature. Removal of acetone afforded a pale yellow solid, which was washed with dichloromethane and acetonitrile to yield **7** as a white solid (0.36 g, 87%). Mp 235–237 °C. ^{1}H NMR (400 MHz, acetone-d_6, room temperature) δ (ppm): 9.43 (d, J=6.8 Hz, 4H), 8.79 (d, J=6.8 Hz, 4H), 8.47 (s, 2H), 7.02 (s, 4H), 6.63 (s, 2H), 5.26 (t, J=4.4 Hz, 4H), 4.76 (t, J=4.4 Hz, 4H), 2.16 (s, 12H). LRESIMS: m/z 685.0 $[M-PF_6]^+$ (100%), 539.0 $[M-PF_6-HPF_6]^+$ (44%). HRESIMS: m/z calcd for $[M-PF_6]^+$ $C_{32}H_{36}F_6N_4O_4P$, 685.2378, found 685.2352, error 3.8 ppm.

4.5. Rotaxane 8

A mixture of bis(*m*-phenylene)-26-crown-8-based cryptand **1** (12.0 mg, 0.019 mmol), paraquat diol **3** (9.2 mg, 0.017 mmol), 3,5-dimethylbenzoic anhydride (19.4 mg, 0.069 mmol), and catalytic amount of trimethylphosphine (Me_3P, 0.26 mg) was dissolved in acetonitrile (0.4 mL). The resulting yellow solution was evaporated in vacuo, whereupon a film developed on the surface of the flask. After 5 min, the evaporation was stopped and the film was left standing in the open air at ambient temperature for 2 h. The mixture was dissolved in acetonitrile and purified by flash column chromatography (CH_2Cl_2/MeOH/$MeNO_2$ 15:1:1 v/v/v) to yield rotaxane **8** as a yellow film (20.7 mg, 85%). ^{1}H NMR (400 MHz, acetone-d_6, room temperature) δ (ppm): 9.41 (d, J=6.4 Hz, 2H), 9.04 (d, J=6.4 Hz, 2H), 8.89 (d, J=6.4 Hz, 2H), 8.39 (d, J=8.0 Hz, 2H), 8.30 (t, J=8.0 Hz, 1H), 8.24 (br s, 2H), 7.75 (s, 2H), 7.57 (s, 2H), 7.29 (s, 1H), 7.21 (s, 1H), 6.42 (s, 2H), 5.51 (s, 2H), 5.47 (d, J=11.2 Hz, 2H), 5.43 (br s, 2H), 5.15 (br s, 4H), 5.07 (br s, 2H), 4.90 (br s, 2H), 4.15 (d, J=11.2 Hz, 2H), 3.18–4.22 (m, 24H), 2.32 (s, 6H), 2.20 (s, 6H). ^{1}H NMR (400 MHz, DMSO-d_6, room temperature) δ (ppm): 9.33 (br s, 2H), 8.93 (br s, 2H), 8.67 (d, J=5.6 Hz, 2H), 8.48 (d, J=8.0 Hz, 2H), 8.36 (t, J=8.0 Hz, 1H), 7.95 (br s, 2H), 7.77 (s, 2H), 7.57 (s, 2H), 7.38 (s, 1H), 7.30 (s, 1H), 6.37 (s, 2H), 5.39–5.42 (m, 4H), 5.29 (br s, 2H), 5.09 (s, 2H), 5.04 (br s, 2H), 4.99 (br s, 2H), 4.84 (br s, 2H), 3.06–4.22 (m, 26H), 2.38 (s, 6H), 2.67 (s, 6H). ^{13}C NMR (100 MHz, acetone-d_6, room temperature) δ (ppm): 166.3, 165.7, 164.7, 159.9, 158.3, 148.6, 147.4, 146.0, 145.4, 145.2, 139.3, 138.6, 138.5, 137.2, 135.3, 135.2, 129.4, 129.0, 128.9, 127.2, 125.9, 109.9, 104.5, 100.9, 70.7, 70.4, 69.8, 69.7, 67.3, 67.2, 66.9, 63.4, 63.1, 60.9, 59.6, 20.3, 20.2. LRESIMS: m/z 574.9 $[M-2PF_6]^{2+}$ (100%). HRESIMS: m/z calcd for $[M-2PF_6]^{2+}$ $C_{65}H_{71}N_3O_{16}$, 574.7417, found 574.7429, error 2.1 ppm.

4.6. Dumbbell-shaped component 9

A solution of 3,5-dimethylbenzoic acid (1.65 g, 11.0 mmol), DCC (2.37 g, 11.5 mmol), and DMAP (0.49 g, 4.00 mmol) in dichloromethane (30 mL) was stirred for 1 h at room temperature, to which was added 2-bromoethanol (1.25 g, 10.0 mmol) in dichloromethane (10 mL). The reaction mixture was stirred for 48 h at room temperature, filtered, and concentrated to give a pale yellow oil, which was purified by flash column chromatography (petroleum ether/ethyl acetate, 30:1 v/v) to provide 2-bromoethyl 3,5-dimethylbenzoate **10** as a colorless oil (2.38 g, 93%). ^{1}H NMR (400 MHz, chloroform-d, room temperature) δ (ppm): 7.68 (s, 2H), 7.21 (s, 1H), 4.61 (t, J=6.4 Hz, 2H), 3.64 (t, J=6.4 Hz, 2H), 2.37 (s, 6H). HRESIMS: m/z calcd for $[M+H]^+$ $C_{11}H_{14}BrO_2$, 257.0177, found 257.0168, error 3.5 ppm. A solution of 2-bromoethyl 3,5-dimethylbenzoate (2.38 g,

9.30 mmol) and 4,4′-bipyridyl (0.48 g, 3.10 mmol) in dry DMF (30 mL) was stirred at 60 °C for 40 h. The resulting precipitate was filtered. The crude yellow solid was then dissolved in deionized water and an aqueous NH_4PF_6 solution was added to precipitate the corresponding salt, which was further purified by flash column chromatography (MeOH/2 M NH_4Cl/$MeNO_2$ 20:2:1 v/v/v) to provide **9** as a white solid (0.56 g, 22%). Mp 241–243 °C. ^{1}H NMR (400 MHz, acetone-d_6, room temperature) δ (ppm): 9.56 (d, J=6.4 Hz, 4H), 8.87 (d, J=6.4 Hz, 4H), 7.55 (s, 4H), 7.24 (s, 2H), 5.39 (t, J=4.8 Hz, 4H), 4.94 (t, J=4.8 Hz, 4H), 2.27 (s, 12H). LRESIMS: m/z 655.0 $[M-PF_6]^+$ (15%), 509.1 $[M-PF_6-HPF_6]^+$ (37%). HRESIMS: m/z calcd for $[M-PF_6]^+$ $C_{32}H_{34}F_6N_2O_4P$, 655.2160, found 655.2162, error 0.3 ppm.

4.7. X-ray crystal data of 1·2·1

Crystallographic data: block, orange, 0.20×0.12×0.10 mm^3, $C_{82}H_{100}F_{12}N_6O_{27}P_2$, *FW* 1891.62, triclinic, space group $P\bar{1}$, a=10.697(2), b=12.361(3), c=17.412(4) Å, α=77.694(6)°, β=77.988(7)°, γ=88.464(9)°, V=2199.8(8) Å^3, Z=1, D_c=1.428 g cm^{-3}, T=113(2) K, μ=0.156 mm^{-1}, 24,374 measured reflections, 8629 independent reflections, 649 parameters, 81 restraints, F(000)=988, R_1=0.0696, wR_2=0.1798 (all data), R_1=0.0593, wR_2=0.1690 [$I>2\sigma(I)$], max. residual density 0.869 e Å^{-3}, and goodness-of-fit (F^2)=1.061. Crystallographic data (excluding structure factors) for the structures in this paper have been deposited with the Cambridge Crystallographic Data Center as supplementary publication numbers CCDC 697656 and 697657. Copies of the data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK [fax: 144 (0)1223 336033 or e-mail: deposit@ccdc.cam.ac.uk].

4.8. X-ray crystal data of 1·3

Crystallographic data: block, yellow, 0.30×0.15×0.09 mm^3, $C_{53}H_{62}F_{12}N_6O_{15}P_2$, *FW* 1313.03, monoclinic, space group $P\ 2_1/c$, a=11.8411(13), b=19.093(2), c=25.949(3) Å, α=90°, β=93.804(7)°, γ=90°, V=5853.8(11) Å^3, Z=4, D_c=1.490 g cm^{-3}, T=90 K, μ=1.649 mm^{-1}, 29,528 measured reflections, 10,247 independent reflections, 802 parameters, 0 restraints, F(000)=2720, R_1=0.0707, wR_2=0.1130 (all data), R_1=0.0536, wR_2=0.1070 [$I>2\sigma(I)$], max. residual density 0.66 e Å^{-3}, and goodness-of-fit (F^2)=0.9749.

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Supplementary data

Electrospray ionization mass spectra of the complexes **1**·**2** and **1**·**3**, NMR spectra and other characterizations of **1**, **6**–**9** and intermediate products, and other materials. Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tet.2008.11.081.

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