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Conformational changes in C$_{methyl}$-resorcinarene
pyridine N-oxide inclusion complexes in the solid state†

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Aromatic N-oxides interact with C$_{methyl}$-resorcinarene resulting in marked changes in the conformation of the host resorcinarene. In the solid state, 2- and 3-methylpyridine N-oxides form pseudo-capsular 2:2 endo host–guest complexes with C$_{methyl}$-resorcinarene stabilized by C–H⋯π interactions. The C$_{methyl}$-resorcinarene-2-methylpyridine N-oxide complex has a C$_{av}$ crown conformation, while the C$_{methyl}$-resorcinarene-3-methylpyridine N-oxide complex has a slightly open C$_{2v}$ boat conformation. On the contrary, other para-substituted and benzo-fused pyridine N-oxides form only exo complexes with C$_{methyl}$-resorcinarene. In the exo complexes, the asymmetry of the guest, conformational flexibility and preferred inter-host hydrogen bonding of C$_{methyl}$-resorcinarenes exclude endo complexation. All the exo complexes form robust 1-D hydrogen bonded chains between the host hydroxyl groups assisted by the guest N=O groups, resulting in a C$_{2v}$-boat conformation.

Other unusual conformations such as the rarely observed rccct-diamond C$_{methyl}$-resorcinarene, the rccct-boat C$_{methyl}$-2-nitroresorcinarene and the rccct-crown C$_{av}$-pyrogallarene (4t=tert-butyl) have been reported. In the C$_{av}$ conformation, intramolecular circular hydrogen bonds (HB) between adjacent phenolic hydroxyl groups preserve the crown structure. In this conformation, the π-rich cavity is suitable for inclusion of spherical and planar guests such as ammonium and phosphonium cations, the main complexation force being the cation⋯π interactions. With resorcinarenes, these cationic guests play a key role in numerous solid-state architectures such as open inclusion complexes, dimers, hexamers and tubular assemblies. Though inclusion complexes of resorcinarenes with cationic compounds are prevalent, there are several reports of complexes with neutral N-heteroaromatic five- and six-membered planar guests as well. N-Aromatic compounds such as 2,2′- and 4,4′-bipyridines, due to their size and strong hydrogen bond acceptor properties, have been particularly effective in inducing conformational changes in resorcinarene complexes. A Cambridge Structural Database (CSD) search using C$_{methyl}$-resorcinarene 1 as the host revealed 34 crystal structures with 4,4′-bipyridine as the guest molecule.

Aromatic N-oxides are well-known synthetic intermediates for functionalization of the pyridine ring in organic synthesis, and as ligands in supramolecular chemistry. The oxygen in the N-oxide group can exhibit hyper-dentate coordination behaviour with metal cations, resulting in interesting supramolecular architectures. Most recently, pyridine N-oxides have been shown to be excellent halogen bond acceptors and thus form very strong halogen bonds.
systems. In this work, we report solid-state complexes with N-capsular assemblies with aromatic N-oxides using C$_{ethyl}$2-methylresorcinarene as the host. Recently, we have reported dimeric pseudo-capsular assemblies with aromatic N-oxides using C$_{ethyl}$2-methylresorcinarene as the host. There exists one study with 4,4'-bipyridine N,N'-dioxide and C$_{methyl}$resorcinarene as the host. In this work, we report solid-state complexes with C$_{methyl}$resorcinarene as the host and seven PyNOs (Fig. 1) as the guests, and the conformational behaviour of the host upon complexation.

Results and discussion

X-ray crystallography

Single crystals of the complexes were obtained from slow evaporation of the methanolic solution of a 1:1 mixture of the host and guest molecules. Attempts to crystallize PyNO, 2,6-DiMePyNO and QNO with 1 were unsuccessful. In the endo complexes, the N-oxide oxygen atoms point away from the cavity (Fig. 2). Complexes of 2-MePyNO and 3-MePyNO with host 1 resulted in mixed endo/exo complexes, 2-MePyNO-1 and 3-MePyNO-1 (Fig. 2), which are remarkably similar to our previous results with C$_{ethyl}$2-methylresorcinarene. Complex 2-MePyNO-1 [formally 1:2-MePyNO]$_{endo}$:3(2-MePyNO)$_{exo}$] can be described as a discrete dimeric pseudo-capsular 2:2 complex which is then hydrogen bonded to six exo-cavity 2-MePyNO molecules, as shown in Fig. 2b. In complex 2-MePyNO-1, host 1 retains the crown conformation (centroid-to-centroid distances being nearly equal, ca. 6.8/7.0 Å, Fig. 3), encapsulating one 2-MePyNO molecule. The guest, 2-MePyNO, resides 3.2 Å from the centroid of the lower rim carbon atoms (calculated from the PyNO benzene ring carbon deepest in the cavity). The hydrogen atoms para to the N-O and –CH$_3$ groups of 2-MePyNO manifest C–H⋯π interactions with the aromatic rings of host 1 with distances ranging between 2.7 Å and 3.1 Å (Fig. 3a). Complex 3-MePyNO-1 [formally 1:3-MePyNO]$_{endo}$:1[3-MePyNO]$_{exo}$] forms a similar dimeric pseudo-capsular 2:2 complex to 2-MePyNO (Fig. 2c). These dimers are hydrogen-bonded to each other by bridging exo 3-MePyNO molecules as shown in Fig. 2d. In complex 3-MePyNO-1, the cavity of host 1 is elongated so that the centroid-to-centroid distances

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Fig. 1  The chemical structures of C$_{methyl}$resorcinarene (1), pyridine N-oxide (PyNO), 2-methylpyridine N-oxide (2-MePyNO), 3-methylpyridine N-oxide (3-MePyNO), 4-methylpyridine N-oxide (4-MePyNO), 2-methyl-4-nitropyridine N-oxide (2-MeNPyNO), 2,6-dimethylpyridine N-oxide (2,6-DiMePyNO), 4-methoxypyridine N-oxide (4-MeOPyNO), 4-phenylpyridine N-oxide (4-PhPyNO), quinoline N-oxide (QNO), and isoquinoline N-oxide (IsQNO).

Fig. 2 (a) Side view of the discrete dimeric structure of 2-MePyNO-1, and (b) top view showing exo-cavity HB monodentate decorated 2-MePyNO with host 1. (c) Section of the 1-D polymeric crystal packing in 3-MePyNO-1 showing endo 3-MePyNO as a bidentate HB acceptor, and the respective (d) side view showing the exo-cavity HB bidentate 3-MePyNO molecules.
are 5.8 and 7.5 Å to accommodate the slightly bigger 3-MePyNO molecule, as shown in Fig. 3d. The endo guest in 3-MePyNO-1 is situated 3.2 Å from the centroid of the lower rim carbon atoms, exactly the same distance as that in 2-MePyNO-1 and previously studied 3-MePyNO-C_{ethyl}2-methylresorcinarene.21 In 3-MePyNO-1, the guest is situated near the center of the cavity between the benzene rings with no apparent aromatic π···π interaction, but manifesting a weak methyl C–H···O hydrogen bond to the host O–H group (C–H···O distance of 2.51 Å) and C–H···π interactions from the hydrogen atoms meta to the N–O group (Fig. 3c). These C–H···π distances range from 2.8 Å to 2.9 Å. The increased conformational flexibility of host 1 and the larger guest size in the endo complexation via the C–H···π interactions between the host and the guest distort the parent C_{4v} crown conformation to a nearly ideal C_{2v} boat conformation (Fig. 3d). With our previous work on resorcinarene endo PyNO complexes,21 the PyNOs located deep in the cavity, viz. <2.9 Å from the centroid of the lower rim carbon atoms, usually show short C–H···π(centroid) contacts. However in 3-MePyNO-1, where the 3-MePyNO guest is situated higher in the cavity (3.2 Å), the shortest C–H···π(centroid) distance of ca. 2.5 Å was observed. Comparing the host–guest chemistry of 2-MePyNO-1 and 3-MePyNO-1 with that of C_{ethyl}2-methylresorcinarene,21 both host systems show a similar encapsulation profile to 2-MePyNO and 3-MePyNO. In general, the formation of endo complexes with host 1 is considerably more difficult than that with conformationally more rigid host molecules due to the stronger influence of the intermolecular hydrogen bonding between the hosts, which can lead to the conformational change and subsequent formation of host-to-host 1-D, 2-D or 3-D networks.

The conformational flexibility of resorcinarenes is due to their lower rim R chains. The methyl chain is smaller, thus allowing more different conformations for the resorcinarene skeleton. The ethyl chain is sterically more bulky and thus results in conformationally less flexible resorcinarenes.2,5 Sterically suitable PyNOs like 2-MePyNO and 3-MePyNO which do form endo complexes with conformationally flexible host systems are also proven to form endo complexes with more rigid systems; this we have recently shown with C_{ethyl}2-methylresorcinarene.21 The question arises if the larger PyNOs21 would also behave similarly to the more flexible host 1. As such, larger PyNOs were utilized to probe their behaviour.
Complexes 4-MePyNO-1 [formally 1:2(4-MePyNO)_{exo}:CH\textsubscript{3}OH], 4-MeOPyNO-1 [formally 1:2(4-MeOPyNO)_{exo}], 2-MeNPyNO-1 [formally 1:2(2-MeNPyNO)_{exo}:4CH\textsubscript{3}OH:H\textsubscript{2}O], 4-PhPyNO-1 [formally 1:2(4-PhPyNO)_{exo}], and IsQNO-1 [formally 1:2(IsQNO)_{exo}:4CH\textsubscript{3}OH:4H\textsubscript{2}O] manifest only exo complexes with a prominent feature being the formation of 1-D tubular hydrogen-bonded chains with a $C_{2v}$ boat conformation of the host (Fig. 3f and g). The asymmetric structure and larger size of these PyNOs prevent the formation of endo complexes and the ease of intermolecular hydrogen bond formation leads to the formation of host-to-host 1-D tubular chains in all complexes, as shown in Fig. 4. During crystallization, the host interactions with themselves, the guest and the solvent molecules (methanol and water) change the conformation from the $C_{4v}$ crown to $C_{2v}$ boat and provide possibilities for better intermolecular hydrogen bonding between the hydroxyl groups of the hosts. Two types of 1-D chains were observed, only PyNOs (type 1) and a combination of PyNOs and solvent molecules (type 2). The type 1 situation appears in complexes 4-MeOPyNO-1 and 4-PhPyNO-1, while type 2 is observed in complexes 2-MeNPyNO-1 and IsQNO-1 (Fig. 5 and ESI† Fig. S6).

In complex 4-MePyNO-1, the 4-MePyNO molecules bridge the hosts via the N-oxide oxygen atom $(O-H)_{\text{host}}\cdot\cdot\cdot(O-N)\cdot\cdot\cdot(O-H)_{\text{host}}$ with distances of 2.60 and 2.67 Å, generating a zigzag 1-D tubular chain (Fig. 5a). A closer look at the 3-D crystal packing reveals that the 4-MePyNO molecules of the 1-D polymeric chain are additionally stabilised by π⋯π interactions at centroid-to-centroid distances of ca. 3.9 Å (ESI† Fig. S1b). Both 4-MeOPyNO-1 and 4-PhPyNO-1 manifest a regular 1-D chain joined by the bidentate N-oxide oxygen atom with $(O-H)_{\text{host}}\cdot\cdot\cdot(O-N)\cdot\cdot\cdot(O-H)_{\text{host}}$ distances of 2.64 Å (4-MeOPyNO-1), and ca. 2.66–2.72 Å (4-PhPyNO-1) as shown in Fig. 5b and c.

Further analysis of the crystal packing shows that the 1-D chains in 4-MeOPyNO-1 and 4-PhPyNO-1 interdigitate to form 2-D supramolecular sheets (see the ESI† Fig. S2). These interdigitated 1-D chains are stabilized by C–H⋯π and π⋯π interactions. During interdigitation, the aromatic rings of host 1, and the hydrogen atoms of the methoxy group in 4-MeOPyNO, and the para hydrogen atoms of 4-PhPyNO have short C–H⋯π contacts with distances of ca. 2.8 Å and 2.7 Å, respectively (see the ESI† Fig. S2 and S3).

The host molecules in complex 2-MeNPyNO-1 also form a 1-D hydrogen bonded chain as shown in Fig. 5d. However, the hydrogen bonding via the hydroxyl groups of the host and the crystal packing differ due to interactions with solvent molecules and a second 2-MeNPyNO molecule in the asymmetric unit. Two methanol molecules, a water molecule and a 2-MeNPyNO molecule hydrogen bond to three host hydroxyl groups of the 1-D tubular chain in a continuous fashion $(O-H)_{\text{host}}\cdot\cdot\cdot(O-H)_{\text{CH}_3\text{OH}}\cdot\cdot\cdot(O-H)_{\text{H}_2\text{O}}\cdot\cdot\cdot(O-H)_{\text{CH}_3\text{OH}}\cdot\cdot\cdot(O-N)_{\text{PyNO}}$. 

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**Fig. 4** Repeating units of the crystal packing viewed along the 1-D chains of complexes 4-MePyNO-1, 4-MeOPyNO-1, 2-MeNPyNO-1, 4-PhPyNO-1, and IsQNO-1 (left to right).

**Fig. 5** Side view of the 1-D HB chains of host 1. (a) 4-MePyNO-1, (b) 4-MeOPyNO-1, (c) 4-PhPyNO-1, (d) 2-MeNPyNO-1 and (e) IsQNO-1. The PyNO molecules are shown in green. The solvent molecules are shown in orange in figures (d) and (e).
(see the ESI,† Fig. S4a). Also, the second 2-MePyNO molecule hydrogen bonds to water and resides close to the host aromatic ring at centroid-to-centroid distances of ca. 3.7 Å. The crystal packing of 2-MePyNO·1 shows that the 1-D chains are connected by two methanol molecules to give a 2-D sheet motif (see the ESI,† Fig. S4c).

The mode of action of the host 1 hydroxyl groups in the 1-D polymeric chain of complex IsQNO·1 (Fig. 5e) is different from other complexes. The host hydroxyl groups are connected by methanol and IsQNO molecules through hydrogen bonds, (O–H)host⋯(O–H)ch,OH−⋯(O–N)IsQNO⋯(O–H)host with distances of ca. 2.61, 2.64 and 2.63 Å, respectively. Once again, the 1-D chains interdigitate by extensive C–H⋯π and π⋯π interactions between IsQNO molecules to give a 2-D sheet (see the ESI,† Fig. S5) motif. During interdigitation, the aromatic rings of IsQNO molecules have centroid-to-centroid distances of ca. 3.9 Å, and C–H⋯π contacts with the host aromatic rings at distances of ca. 2.8 Å.

Solution studies
Solution studies between host 1 and PyNO, 2-MePyNO, 3-MePyNO, 4-MePyNO, 2-MeNPyNO, 2,6-DiMePyNO, 4-MeOPyNO, 4-PhPyNO, QNO and IsQNO as guests were conducted via 1H NMR experiments in CD3OD at 293 K. In these experiments, the host and guests were mixed in a 1:1 (6.6 mM on both molecules) ratio in CD3OD; the 1H NMR spectra were measured and the results were compared with the free host (6.6 mM) and free guests (6.6 mM).

Complexation-induced shielding of the guest proton resonances was observed in all cases except with 4-PhPyNO. The shielding effects of the aromatic rings of the bowl-shaped host cavity upon addition of the guest are responsible for this upfield shift and indicate that guest exchange is fast on the NMR time scale. Taking the 1:1 mixture between 1 and 3-MePyNO as an example (Fig. 6, I), the aromatic protons (g, f) are the most shielded (0.16 ppm and 0.17 ppm). These shift changes confirm the orientation of the guest deep in the host cavity, supporting the X-ray crystal structure (Fig. 3). Analysis of the 1:1 mixture between 1 and QNO (Fig. 6, II) reveals the aromatic protons (f, g) to be the most shielded (0.14–0.15 ppm), once again suggesting the localization of QNO within the host cavity. The analyses of the 1H NMR results between the host and the other guests (PyNO, 2-MePyNO, 4-MePyNO, 2-MeNPyNO, 2,6-DiMePyNO, 4-MeOPyNO, and IsQNO) also indicate the localization of the guest in the host cavity (Fig. S7–S16†). No shift changes were observed with 4-PhPyNO, implying that in solution no host–guest complex is formed (Fig. S14†).

Variable temperature (233–333 K) 1H NMR experiments were done to probe the conformational changes of host 1 in the presence of the different guests (Fig. S17–S18†). No obvious changes in the host 1 signals were observed, implying that the conformational changes observed in the solid state with the N-oxide guests are caused by multiple intermolecular interactions existing only in the solid state.

Conclusions
The X-ray structures of seven PyNO complexes led to the conclusion that there is either endo complexation via C–H⋯π interactions or exo complexation via (N–O)⋯(H–O)host hydrogen bonds between the aromatic N-oxides and Cmethyl-resorcinarene. Due to the rarity of Cmethyl-resorcinarene-pyridine N-oxide complexes, the endo host–guest complexes 2-MePyNO·1 and 3-MePyNO·1 were compared with our previous results with Cethyl-2-methylresorcinarene,21 which allowed us to probe factors such as the conformational flexibility of the cavity, the strength of C–H⋯π interactions and the localization of the guest molecule in the cavity. Despite the enhanced conformational flexibility, Cmethyl-resorcinarene forms a pseudo-capillary 2:2 endo complex with 2-MePyNO and 3-MePyNO stabilized by C–H⋯π interactions in the solid state. The larger overall size of 3-MePyNO forces the C2v crown conformation to open, very close to the ideal C2v boat conformation, but still having the guest inside the cavity. Additionally, the strong C–H⋯π interactions found in the endo complex 3-MePyNO·1 hint that the guest similar to 3-MePyNO with Cmethyl-resorcinarene could show interesting host–guest interactions. The larger guests 4-MePyNO, 2-MeNPyNO, 4-MeOPyNO, 4-PhPyNO and IsQNO do not form endo complexes, as the exo complexes are preferred due to the strong intermolecular hydrogen bonding between the host 1 molecules leading to 1-D chains. All exo complexes show very similar overall crystal packings. The complementary solution studies show that host–guest complexes between host 1 and all the N-oxide molecules, except 4-PhPyNO, are formed in solution. Furthermore, the variable temperature 1H NMR
measurements proved that the conformational changes in host I, observed in the solid state upon complexation, were not observed in solution.

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Notes and references
13 CSD version 5.36 (November 2014), ConQuest Version 1.17; Search performed date, 17.12.2015. The CSD search was defined and limited to core C_methylresorcinarene as the host molecule.