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# Inclusion complexes of $C_{\text{ethyl}}$ -2-methylresorcinarene and pyridine $N$ -oxides: breaking the $C-I\cdots O-N^+$ halogen bond by host-guest complexation†

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$C_{\text{ethyl}}$ -2-Methylresorcinarene forms host-guest complexes with aromatic  $N$ -oxides through multiple intra- and intermolecular hydrogen bonds and  $C-H\cdots\pi$  interactions. The host shows conformational flexibility to accommodate 3-methylpyridine  $N$ -oxide, while retaining a crown conformation for 2-methyl- and 4-methoxypyridine  $N$ -oxides highlighting the substituent effect of the guest.  $N$ -Methylmorpholine  $N$ -oxide, a 6-membered ring aliphatic  $N$ -oxide with a methyl at the  $N$ -oxide nitrogen, is bound by the equatorial  $-N-CH_3$  group located deep in the cavity. 2-Iodopyridine  $N$ -oxide is the only guest that manifests intermolecular  $N-O\cdots I-C$  halogen bond interactions, which are broken down by the host resulting in a 2:2 pseudocapsular complex stabilized by additional  $C-I\cdots\pi$  interactions between the two 2-iodopyridine  $N$ -oxides located in two adjacent hosts. These host-guest complexes were analyzed in the solid state by single crystal X-ray crystallography and in solution by  $^1H$  NMR spectroscopy.

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## Introduction

Resorcinarenes represent a unique family of host compounds, which are extensively studied in host-guest chemistry due to their  $\pi$ -rich electron cavity in the  $C_{4v}$  conformation.<sup>1</sup> In the  $C_{4v}$  conformation, the bowl shaped cavity of resorcinarenes accommodates a wide range of guest molecules *via* non-covalent interactions such as cation $\cdots\pi$ ,  $C-H\cdots\pi$  and  $\pi\cdots\pi$  interactions depending upon the size and charge distribution of the guest molecules.<sup>2</sup> Besides lattice stabilization, the phenolic groups participate in hydrogen bonds (HBs) with appropriate guest molecules during complexation.<sup>2</sup> As a result, the construction of hydrogen bonded supramolecular networks utilizing resorcinarenes as the key components has been studied with alcohols,<sup>3</sup> sugars,<sup>4</sup> steroids,<sup>5</sup> as well as heterocyclic five- and six-membered ring compounds<sup>6</sup> as guest molecules.

Pyridine  $N$ -oxides (PyNOs) are widely recognized as synthetic intermediates for the functionalization of pyridine rings in organic synthesis.<sup>7</sup> This is due to the specific

electronic nature of the  $^+N-O^-$  group which makes the aromatic ring electron deficient and thus a very interesting guest molecule with electron-rich host systems.<sup>8</sup> Alternatively, the structural and electronic properties of these  $N$ -oxide compounds with the polar  $^+N-O^-$  group make them excellent hydrogen bond acceptors.<sup>9</sup> In spite of the increasing number of reports on PyNO complexes with calixarenes<sup>8a,10</sup> and cavitands,<sup>8b,11</sup> reports on the host-guest chemistry of  $N$ -oxides and resorcinarenes are very rare.<sup>8c,12</sup> The reports on host-guest complexes between  $C_{\text{ethyl}}$ -2-methylresorcinarene and aromatic  $N$ -oxides have highlighted the importance of  $\pi\cdots\pi$  and  $C-H\cdots\pi$  interactions with the PyNOs located inside the  $C_{\text{ethyl}}$ -2-methylresorcinarene cavity.<sup>8c</sup> These observations prompted us to further probe  $C_{\text{ethyl}}$ -2-methylresorcinarene as a reaction vessel to control the coordination sphere of copper(II) in the multicomponent reactions of PyNO copper(II) complexes.<sup>12</sup> The  $\pi\cdots\pi$ ,  $C-H\cdots\pi$  and HB interactions held the PyNOs in the  $C_{\text{ethyl}}$ -2-methylresorcinarene cavity thus controlling the geometry around copper(II).<sup>12</sup> The  $\pi$ -rich nature of  $C_{\text{ethyl}}$ -2-methylresorcinarene and the  $\pi$ -deficient nature of the PyNO guests with multiple HB interaction sites make them a perfect pair for host-guest complexation. Thus, exploring a range of structurally and electronically different aromatic  $N$ -oxides with subtle changes in their structure and the ability to template supramolecular host-guest complexes with  $\pi$ -rich host compounds will give a crystal engineering tool to study the intermolecular interactions involved. Despite the numerous

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literature reports on resorcinarenes, only a handful of crystal structures<sup>13</sup> containing *C*<sub>ethyl</sub>-2-methylresorcinarene (**1**) can be found in the Cambridge Crystallographic Database (CSD). Furthermore, there has been no systematic study on host-guest complexes between PyNOs as guests and any member of the resorcinarene family as the host.

In the present study, we explore five different host-guest systems utilizing *C*<sub>ethyl</sub>-2-methylresorcinarene (**1**) as the host and five structurally and electronically different PyNOs as guests (Fig. 1). *C*<sub>ethyl</sub>-2-Methylresorcinarene (**1**) adopts the *C*<sub>4v</sub> crown conformation in the solid state.<sup>3a,8c,12</sup> Initially, we used 2-methylpyridine *N*-oxide (2MePyNO) and 3-methylpyridine *N*-oxide (3MePyNO) to get insight into the effect of substituents on the structure of the host-guest complexes. 4-Methoxypyridine *N*-oxide (4MeOPyNO) was utilized to study the electronic influence of oxygen atom as a *para*-substituent. *N*-Methylmorpholine *N*-oxide (NMO) was also used as a guest to study the influence of the methyl group at the <sup>+</sup>N–O<sup>−</sup> group within an alicyclic ring system.

As the electron-deficient aromatic ring system in PyNOs will polarize the iodine atom in *ortho*-iodopyridine *N*-oxide (2-IPyNO) and thus induce possible halogen bonding,<sup>14</sup> it was selected as the fifth and multifunctional guest. Based on previous reports, the halogen bond (XB) between the donor part (the iodine atom) and the XB acceptor part (the *N*-oxide oxygen) of 2-IPyNO was envisaged.<sup>15</sup> Based on earlier studies on halo-PyNOs,<sup>15</sup> the self-complementary XB between the XB donor part (the iodine atom) and the XB acceptor part (the *N*-oxide oxygen) of 2-IPyNO was envisaged. The hypothesis was to probe if in the complex between 2-IPyNO and *C*<sub>ethyl</sub>-2-methylresorcinarene the resorcinarene host would be able to break the moderately strong dimeric C–I<sup>−</sup>⋯O<sup>−</sup>N<sup>+</sup> XB by forming a stronger 1:1 2-IPyNO:1 complex. The obtained host-guest complexes were analysed in the solid state by single crystal X-ray diffraction and in solution by <sup>1</sup>H NMR spectroscopy.

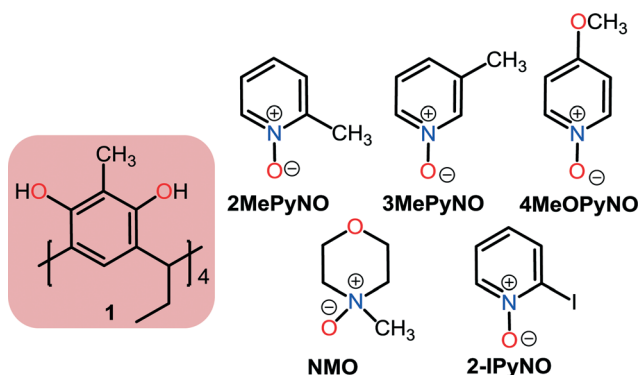


Fig. 1 The chemical structures of *C*<sub>ethyl</sub>-2-methylresorcinarene (**1**), 2-methylpyridine *N*-oxide (2MePyNO), 3-methylpyridine *N*-oxide (3MePyNO), 4-methoxypyridine *N*-oxide (4MeOPyNO), *N*-methylmorpholine *N*-oxide (NMO) and 2-iodopyridine *N*-oxide (2-IPyNO).

## Results and discussion

### X-ray crystallography

Complexes 2MePyNO@1 and 3MePyNO@1 crystallized (see the ESI† for experimental procedures) in the monoclinic space group *P*2<sub>1</sub>/*n* and in the triclinic space group *P* $\bar{1}$ , respectively. In both cases, there are two molecules of *N*-oxides in the asymmetric unit, one sitting inside the cavity and the other outside the cavity. In complex 2MePyNO@1, one 2MePyNO sits inside the cavity with the N–O group pointing up, and is a bifurcated HB acceptor for two host –OH groups [*d*(O–H⋯O), 2.679(3) Å and 2.674(3) Å; ∠O–H⋯O, 159° and 166°], as shown in Fig. 2b. The exo-cavity 2MePyNO directly interacts with the –OH group of host 1 [*d*(O–H⋯O), 2.551(3) Å; ∠O–H⋯O, 160°] *via* a monodentate hydrogen bond (Fig. 2a). All the O⋯O distances are below the sum of the van der Waals radii of oxygen atoms, and clearly the

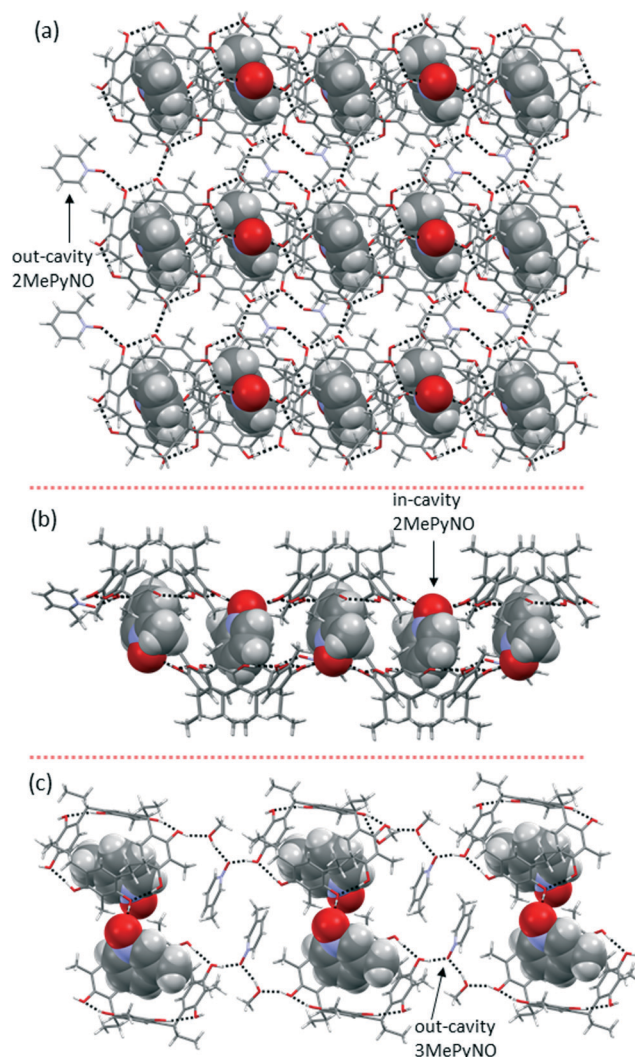


Fig. 2 (a) 2-D polymeric structure of 2MePyNO@1, and (b) side view showing in-cavity 2MePyNO bridging two host molecules by O–H⋯O interactions as a bidentate HB acceptor. (c) Section of the crystal packing in 3MePyNO@1 showing the exo-cavity 3MePyNO as a bidentate HB acceptor.



monodentate HB interaction is stronger than the bidentate HB. Along the *a*-direction, the –OH groups of host 1 form HB by  $(\text{O-H})_{\text{host}} \cdots (\text{O-H})_{\text{host}}$  interactions to give a 2-D polymeric sheet-like structure with the exo-cavity 2MePyNO being a passive spectator, as shown in Fig. 2a. 3MePyNO@1 forms a complex 2-D HB network with the in-cavity 3MePyNO being monodentate and directly hydrogen bonded to the host –OH group [ $d(\text{O-H} \cdots \text{O})$  2.659(7) Å;  $\angle \text{O-H} \cdots \text{O}$ , 171°]. The exo-cavity 3MePyNO together with the methanol molecule connects 3MePyNO@1 units by  $(\text{O-H})_{\text{host}} \cdots (\text{O-H})_{\text{CH}_3\text{OH}} \cdots \text{O}_{\text{py}} \cdots (\text{H-O})_{\text{host}}$  interactions, as shown in Fig. 2c.

*C*<sub>ethyl</sub>-2-Methylresorcinarene (1) exhibits remarkable conformational flexibility due to the positioning of the methyl substituents in 2MePyNO and 3MePyNO, thus resulting in varied C–H $\cdots\pi$  interactions.<sup>16</sup> The *para*- and *meta*-protons of 2MePyNO (Fig. 3a) show C–H $\cdots\pi$  interactions at distances of *ca.* 2.785 Å [ $\angle \text{C-H} \cdots \text{C}$ , 149°] and 2.826 Å [ $\angle \text{C-H} \cdots \text{C}$ , 163°], respectively. On the other hand, in complex 3MePyNO@1, the *meta*- and –CH<sub>3</sub> hydrogens of 3MePyNO show C–H $\cdots\pi$  interactions at distances of *ca.* 2.752 Å [ $\angle \text{C-H} \cdots \text{C}$ , 160°] and 2.863 Å [ $\angle \text{C-H} \cdots \text{C}$ , 162°], respectively. As shown in Fig. 3c, the hydrogen of the –CH<sub>3</sub> group to the centroid of the aromatic ring has the shortest contact at distances of *ca.* 2.715 Å [ $\angle \text{C-H} \cdots \pi(\text{centroid})$ , 147°]. Guests with substituents close to the N–O group sit deep in the cavity. As a result, 2MePyNO sits at a height of 2.818 Å, while 3MePyNO at distances of 3.126 Å from the centroids of the lower rim carbon atoms of host 1. Furthermore, 2MePyNO with an approximately 60° angle between the N–O and methyl groups sits inside the host cavity

without deformation resulting in near similar centroid-to-centroid [6.923 Å and 6.827 Å] distances between opposite aromatic rings (Fig. 3c). However, 3MePyNO with an approximately 120° angle caused significant changes in the host centroid-to-centroid distances between opposite aromatic rings [7.342 Å and 6.226 Å], as shown in Fig. 3d.

Complex 4MeOPyNO@1 forms a 2-D polymeric sheet structure with a 1:1 host-guest ratio. In 4MeOPyNO@1, the N–O group of 4MeOPyNO is pointing up and is bidentate with  $\text{N-O} \cdots (\text{O-H})_{\text{host}}$  and  $\text{N-O} \cdots (\text{O-H})_{\text{CH}_3\text{OH}}$  interactions at distances of 2.650(3) Å [ $\angle \text{O-H} \cdots \text{O}$ , 158°] and 2.580(3) Å [ $\angle \text{O-H} \cdots \text{O}$ , 175°], respectively (Fig. 4a). The extent of the HB interaction of 4MeOPyNO and 2MePyNO with the host –OH groups are very similar. Unlike 2MePyNO@1 and 3MePyNO@1, no C–H $\cdots\pi(\text{host})$  interactions between the aromatic ring protons of 4MeOPyNO and *C*<sub>ethyl</sub>-2-methylresorcinarene (1) are observed. Moreover, the in-cavity –OCH<sub>3</sub> group also assists the 3D crystal packing by weak  $\text{O} \cdots \text{H-C}$  interactions with the adjacent *C*<sub>ethyl</sub> chain of the host.

Complex NMO@1 contains in-cavity and exo-cavity NMO molecules. The in-cavity N–O group and the host –OH group are connected by two methanol molecules while the exo-cavity NMO directly HB to the –OH group of host 1 (Fig. 4b). The difference in host cavity distortions depends on the guest height situated in the cavity, *viz.* 3.077 Å for 4MeOPyNO and 2.920 Å for NMO. In both cases, the guest molecules are situated to the corner of the host, stabilized *via* C–H $\cdots\pi$  interactions. In 4MeOPyNO@1, the –OCH<sub>3</sub> group and the host aromatic ring are stabilized by C–H $\cdots\pi$  interactions at distances

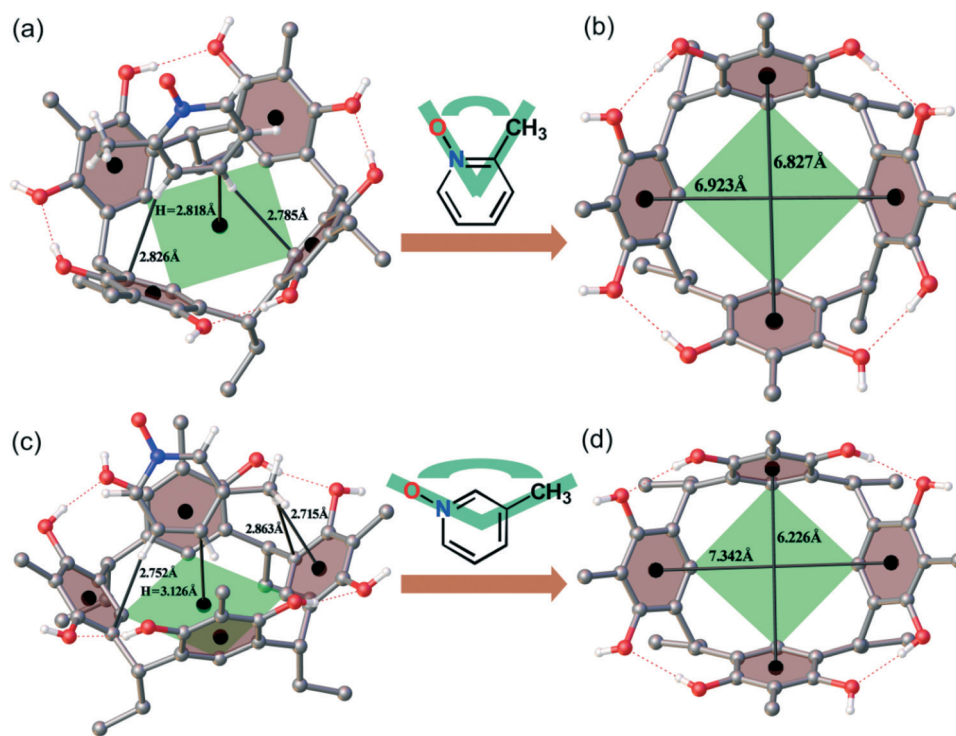
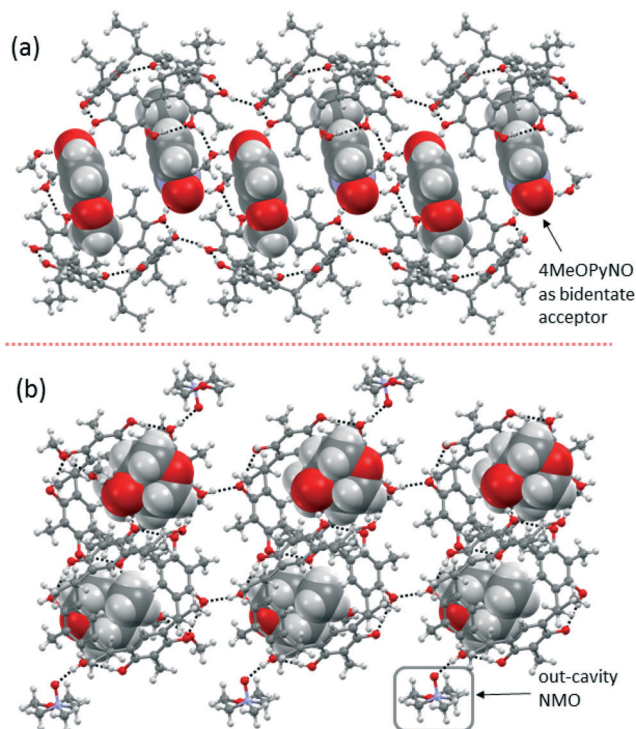


Fig. 3 (a) C–H $\cdots\pi$  interactions in 2MePyNO@1. (b) The cavity of host 1 in 2MePyNO@1 to highlight the flexibility. (c) C–H $\cdots\pi$  interactions in 3MePyNO@1. (d) The cavity of host 1 in 3MePyNO@1 to highlight the flexibility.



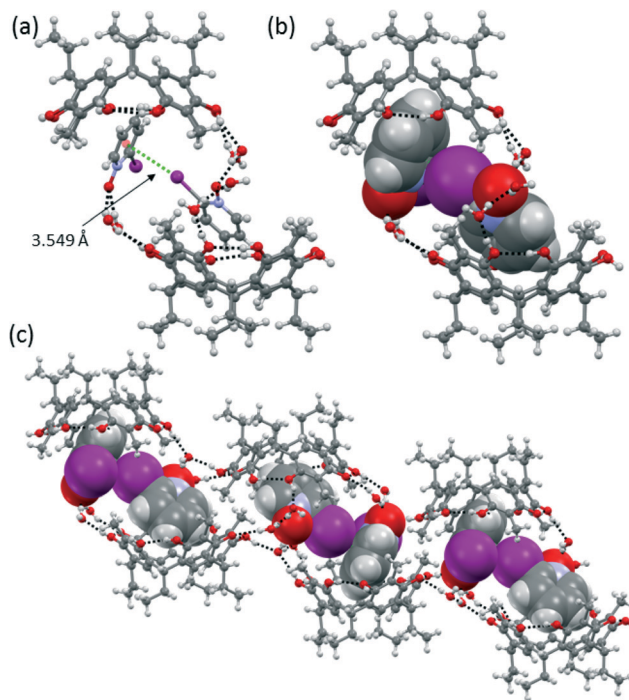




**Fig. 4** (a) Section of the crystal packing in 4MeOPyNO@1 showing O-H...O interactions of 4MeOPyNO and methanol molecules. (b) Top view of the 2D polymeric structure in NMO@1. Black broken lines represent O-H...O interactions.

ranging between 2.919 Å and 3.129 Å, of which C-H...centroid was observed to have the shortest contact with a distance of 2.681 Å (Fig. S4a†). In NMO@1, the in-cavity NMO interacts with the host aromatic ring through C-H... $\pi$  at distances of 2.937 Å and 3.221 Å (Fig. S4b†). The N-O group appears to be the reason for the presence of the in-cavity -N-CH<sub>3</sub> group, which makes NMO a unique guest molecule from other N-oxides.

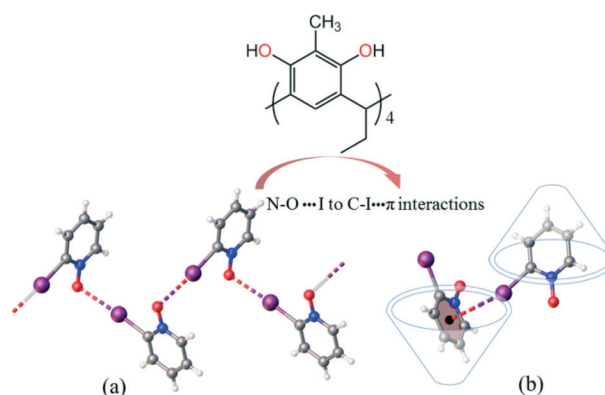
Complex 2-IPyNO@1 reveals a pseudo-capsular arrangement as shown in Fig. 5. The asymmetric unit contains two *C*<sub>ethyl</sub>-2-methylresorcinarenes, each accommodating 2-IPyNO molecules together with six exo-cavity water molecules. The N-O groups of in-cavity 2-IPyNO acts as bidentate and tridentate (Fig. S5†) HB acceptors for the exo-cavity water and adjacent host molecules in stabilizing the pseudo-capsular arrangements by O-H...O interactions. One of the iodines in the cavity of one host interacts with the phenyl ring of the 2-IPyNO located in the cavity of the second host through intermolecular C-I... $\pi$  contacts at distances of 3.549 Å [ $\square$ C-I... $\pi$  (centroid), 161° and  $\square$ C-I... $\pi$  (plane), 155°]. The height of the capsule, defined as the distance between the centroids of the lower rim carbons, is 13.479 Å (Fig. S6†),<sup>8c</sup> in which the two 2-IPyNO molecules are accommodated at heights of 2.720 Å and 3.153 Å. The hosts adopt a distorted crown conformation with centroid-to-centroid distances of 6.790/6.960 Å and 6.816/6.961 Å (Fig. S7†). The height and orientation of the 2-IPyNO molecules increase the number of C-H... $\pi$  interactions with the host aromatic ring. The 2-IPyNO parallel to the host



**Fig. 5** Pseudo capsular arrangement of 2-IPyNO@1 with 2-IPyNO guests shown in (a) ball and stick, and (b) CPK model. (c) Section of the crystal packing showing O-H...O interaction templated 2-IPyNO@1 complexes. Black and green broken lines represent O-H...O and C-I... $\pi$  interactions, respectively.

aromatic ring and situated at a height of 3.153 Å is stabilized by two C-H... $\pi$  interactions, while the non-parallel 2-IPyNO situated deep in the cavity at a height of 2.720 Å is stabilized uniquely by three C-H... $\pi$  interactions (Fig. S7†).

The orientation of the guest aromatic ring deep in the host cavity with the N-O group pointing up has been a primary prerequisite to encapsulate PyNOs by *C*<sub>ethyl</sub>-2-methylresorcinarene (1). As a consequence, the guest molecules become responsive to these interactions. As such, the self-assembly process can be controlled with respect to the guest



**Fig. 6** (a) 1-D polymeric N-O...I interaction based XB complex of 2-IPyNO, and (b) confined C-I... $\pi$  interactions between 2-IPyNO by *C*<sub>ethyl</sub>-2-methylresorcinarene (1) inside complex 2-IPyNO@1.



interactions. To illustrate this, **2-IPyNO** was crystallised under similar solvent conditions to compare the nature of guest interactions in the absence of *C*<sub>ethyl</sub>-2-methylresorcinarene (**1**). The crystal structure of **2-IPyNO** (Fig. 6) displays a classical intermolecular N–O⋯I–C XB at distances of 2.791 Å with an XB ratio ( $R_{\text{XB}} = d_{\text{XB}}/(X_{\text{vdw}} + B_{\text{vdw}})$ ) of 0.791.<sup>14</sup>

The type and strength of the electron withdrawing group attached to the aromatic ring and its influence on the hybridization of the aromatic ring affect the polarization of the halogen atom (usually Br or I) acting either as an electron donor or acceptor. Although iodine has weak interactions with *ortho*-carbons [ $d(\text{C} \cdots \text{C})$ , 3.716 Å;  $\angle \text{C} \cdots \text{C}$ , 141.30°] and nitrogen [ $d(\text{C} \cdots \text{N})$ , 3.649 Å;  $\angle \text{C} \cdots \text{N}$ , 141.28°] of the pyridine *N*-oxide ring, the centroid of the aromatic ring is influenced by the shortest contact with a distance of 3.549 Å. Thus, the iodine substituent clearly demonstrates the presence of weak C–I⋯ $\pi$  halogen type interactions which are enhanced inside the pseudo capsular arrangement.

A CCDC search was carried out to survey the type and nature of molecules involved during intermolecular C–I⋯aromatic ring interactions. The first search was limited to any 2-substituted iodo-aromatic compounds and their non-bonded interactions with an adjacent aromatic ring. In total, 22 hits were found,<sup>13d,17</sup> and of all the structures, one of those reported constitutes the shortest distance of 3.321 Å.<sup>17o</sup> A search for perfluorinated iodobenzene related C–I⋯ $\pi$  interactions revealed zero hits. Consequently, individual surveys were carried out on compounds that have neutral aprotic electron-withdrawing groups (–F, –Cl, –NO<sub>2</sub>, –CN, –CF<sub>3</sub>, –CCl<sub>3</sub> and –COCl) and electron donating groups (alkyl and –NR<sub>2</sub>) at the 2-substituted position of iodo-aromatic compounds. Only the chloro substituent retrieved one hit, which has a C–I⋯ $\pi$  distance of 3.537 Å.<sup>18</sup>

## NMR analyses

Solution studies between *C*<sub>ethyl</sub>-2-methylresorcinarene (**1**) as the host and **2MePyNO**, **3MePyNO**, **4MeOPyNO**, **NMO**, and **2-IPyNO** as the guests were conducted *via* <sup>1</sup>H NMR experiments in CD<sub>3</sub>OD at room temperature. In the experiments, 1:1 and 1:2 mixtures of the host and guests were prepared; the <sup>1</sup>H NMR spectra were measured and the results were compared with the free host (6.6 mM) and free guests (6.6 mM).

Significant complexation-induced shielding of the guest proton resonances was observed in all cases. 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 clearly point to a fast guest exchange on the NMR time scale. Taking the 1:1 mixture between *C*<sub>ethyl</sub>-2-methylresorcinarene (**1**) and **NMO** as an example (Fig. 7), the methyl group protons (e) are the most shielded (0.76 ppm). These shift changes clearly confirm the orientation of the guest in the host cavity. The large shift change for the methyl protons suggests that the protons are situated deep in the cavity of the host. This is analogous to the X-ray structure (Fig. 4b).

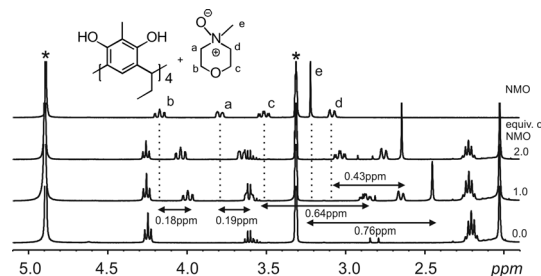


Fig. 7 Selected region of the <sup>1</sup>H NMR spectra (CD<sub>3</sub>OD, room temperature) after the addition of up to 2 equivalents of **NMO** to host **1**. Stars represent the residual CD<sub>3</sub>OD. The shift changes of the guest signals in ppm are highlighted.

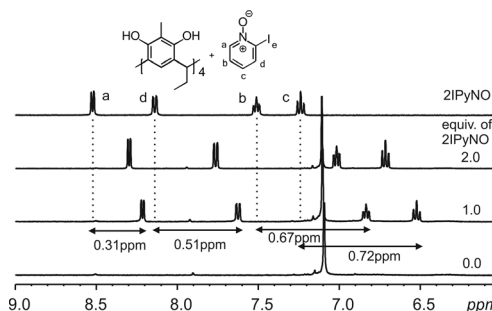


Fig. 8 Selected region of the <sup>1</sup>H NMR spectra (CD<sub>3</sub>OD, room temperature) after the addition of up to 2 equivalents of **2-IPyNO** to host **1**. Stars represent the residual CD<sub>3</sub>OD. The shift changes of the guest signals in ppm are highlighted.

Analyses of the 1:1 mixture between *C*<sub>ethyl</sub>-2-methylresorcinarene (**1**) and **2-IPyNO** (Fig. 8) reveal the aromatic protons (b, c) to be the most shielded (0.67–0.72 ppm) with the proton next to the –NO group the least shielded (0.31 ppm). This supports the orientation of the guest within the host cavity as seen from the X-ray structures (Fig. 5 and 6). The analyses of the <sup>1</sup>H NMR results between the host and the other guests (**2MePyNO**, **3MePyNO** and **4MeOPyNO**) also confirm the orientation of the guests in the host cavity (Fig. S1–S3†) and support the structures observed from solid state analyses (Fig. 2 and 4). Additionally, the flexibility of the host when accommodating the guest is observed from the small changes in the host upper rim methyl groups and the aromatic protons upon complex formation. This again supports the observation from solid-state studies.

## Conclusions

Five host–guest complexes between *C*<sub>ethyl</sub>-2-methylresorcinarene (**1**) and five different *N*-oxides, three aromatic (**2MePyNO**, **3MePyNO**, and **4MeOPyNO**), one aliphatic (**NMO**) and 2-iodopyridine *N*-oxide (**2-IPyNO**), were obtained and analysed in the solid state and in solution *via* single crystal X-ray diffraction studies and <sup>1</sup>H NMR analyses, respectively. The conformational flexibility of the host was observed when *ortho*- and *meta*-methylated guest molecules were utilized. All the aromatic guests were located in the cavity such that the



N–O groups point upwards (out of the cavity). However, the aliphatic analogue **NMO** reveals the equatorial –N–CH<sub>3</sub> group to be located deep in the cavity of the host, which greatly changes the cavity size and conformation of the host. The 1-D polymeric halogen bonded complex was disrupted in the presence of the host, resulting in a 2:2 host-guest pseudo capsular complex when 2-iodopyridine *N*-oxide (**2-IPyNO**) was used. Extra C–I $\cdots\pi$  interactions between the two **2-IPyNO** located in two different hosts help to glue the two capsule halves. In all the complexes, the binding of the *N*-oxides proceeds through multiple intra- and intermolecular hydrogen bonds, –C–H $\cdots\pi$ ,  $\pi\cdots\pi$  and –C–I $\cdots\pi$  interactions. The solution analyses through <sup>1</sup>H NMR measurements clearly support the structures observed in the solid state. Aromatic and aliphatic *N*-oxides are proving to be suitable guest compounds for the resorcinarene cavity when in the *C*<sub>4v</sub> conformation. *N*-Oxides have huge potential with numerous applications as ligands in organo-metallic chemistry. Their ability to interact with resorcinarenes implies that they can be utilized in tandem to tune and construct functional assemblies.

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## Notes and references

- (a) P. Timmerman, W. Verboom and D. N. Reinhoudt, *Tetrahedron*, 1996, **52**, 2663–2704; (b) V. Böhmer, *Angew. Chem., Int. Ed. Engl.*, 1995, **34**, 713–745; (c) K. Rissanen, *Angew. Chem., Int. Ed.*, 2005, **44**, 3652–3654.
- (a) J. L. Atwood and A. Szumna, *Chem. Commun.*, 2003, 940–941; (b) J. L. Atwood, L. J. Barbour and A. Jerga, *Proc. Natl. Acad. Sci. U. S. A.*, 2002, **99**, 4837–4841; (c) L. R. MacGillivray and J. L. Atwood, *Chem. Commun.*, 1999, 181–182; (d) A. Shivanyuk, E. F. Paulus, K. Rissanen, E. Kolehmainen and V. Böhmer, *Chem. – Eur. J.*, 2001, **7**, 1944–1951; (e) N. K. Beyeh, M. Kogej, A. Åhman, K. Rissanen and C. A. Schalley, *Angew. Chem., Int. Ed.*, 2006, **45**, 5214–5218.
- (a) N. K. Beyeh, D. P. Weimann, L. Kaufmann, C. A. Schalley and K. Rissanen, *Chem. – Eur. J.*, 2012, **18**, 5552–5557; (b) L. Avram, Y. Cohen and J. Rebek Jr., *Chem. Commun.*, 2011, **47**, 5368–5375; (c) I. A. Koshets, Z. I. Kazantseva, A. E. Belyaev and V. I. Kalchenko, *Sens. Actuators, B*, 2009, **140**, 104–108; (d) O. Ugono and K. T. Holman, *Chem. Commun.*, 2006, 2144–2146; (e) O. D. Fox, J. F.-Y. Leung, J. M. Hunter, N. K. Dalley and R. G. Harrison, *Inorg. Chem.*, 2000, **39**, 783–790.
- (a) E. Kalenius, T. Kekäläinen, R. Neitola, K. Beyeh, K. Rissanen and P. Vainiotalo, *Chem. – Eur. J.*, 2008, **14**, 5220–5228; (b) M. He, R. J. Johnson, J. O. Escobedo, P. A. Beck, K. K. Kim, N. N. S. Luce, C. J. Davis, P. T. Lewis, F. R. Fronczek, B. J. Melancon, A. A. Mrse, W. D. Treleaven and R. M. Strongin, *J. Am. Chem. Soc.*, 2002, **124**, 5000–5009; (c) T. Evan-Salem, I. Baruch, L. Avram, Y. Cohen, L. C. Palmer and J. Rebek, *Proc. Natl. Acad. Sci. U. S. A.*, 2006, **103**, 12296–12300; (d) T. Rhlalou, M. Ferhat, M. A. Frouji, D. Langevin, M. Métayer and J.-F. Verchère, *J. Membr. Sci.*, 2000, **168**, 63–73.
- (a) A. Shivanyuk and J. Rebek, *Chem. Commun.*, 2001, 2374–2375; (b) J. D. Faull and V. K. Gupta, *Thin Solid Films*, 2003, **440**, 129–137; (c) J. D. Faull and V. K. Gupta, *Langmuir*, 2002, **18**, 6584–6592.
- (a) M. Nissinen, E. Wegelius, D. Falábu and K. Rissanen, *CrystEngComm*, 2000, **2**, 151; (b) M. Nissinen and K. Rissanen, *Supramol. Chem.*, 2003, **15**, 581–590.
- (a) A. E. V. Gorden, J. Xu, K. N. Raymond and P. Durbin, *Chem. Rev.*, 2003, **103**, 4207–4282; (b) R. R. Schrock, *Chem. Rev.*, 2002, **102**, 145–180; (c) J. A. Pool, B. L. Scott and J. L. Kiplinger, *J. Am. Chem. Soc.*, 2005, **127**, 1338–1339.
- (a) G. Zheng, Y.-Y. Li, H.-D. Guo, S.-Y. Song and H.-J. Zhang, *Chem. Commun.*, 2008, 4918–4920; (b) L. Adriaenssens and P. Ballester, *Chem. Soc. Rev.*, 2013, **42**, 3261–3277; (c) N. K. Beyeh, R. Puttreddy and K. Rissanen, *RSC Adv.*, 2015, **5**, 30222–30226.
- (a) N. J. Babu, L. S. Reddy and A. Nangia, *Mol. Pharmaceutics*, 2007, **4**, 417–434; (b) N. R. Goud, N. J. Babu and A. Nangia, *Cryst. Growth Des.*, 2011, **11**, 1930–1939; (c) S. G. Bodige, M. A. Zottola, S. E. McKay and S. C. Blackstock, *Cryst. Eng.*, 1998, **1**, 243–253; (d) M. Muthuraman, R. Masse, J.-F. Nicoud and G. R. Desiraju, *Chem. Mater.*, 2001, **13**, 1473–1479.
- (a) B. Verdejo, G. Gil-Ramírez and P. Ballester, *J. Am. Chem. Soc.*, 2009, **131**, 3178–3179; (b) G. Zheng, W. Fan, S. Song, H. Guo and H. Zhang, *J. Solid State Chem.*, 2010, **183**, 1457–1463; (c) G. W. Orr, L. J. Barbour and J. L. Atwood, *Science*, 1999, **285**, 1049–1052; (d) B.-T. Zhao, H. Wang, H.-Y. Zhang and Y. Liu, *J. Mol. Struct.*, 2005, **740**, 101–105; (e) K. Xiong, F. Jiang, M. Wu, Y. Gai, Q. Chen, S. Zhang, J. Ma, D. Han and M. Hong, *J. Solid State Chem.*, 2012, **192**, 215–220; (f) J. L. Atwood, G. W. Orr and K. D. Robinson, *Supramol. Chem.*, 1994, **3**, 89–91.
- A. Galán, E. C. Escudero-Adán, A. Frontera and P. Ballester, *J. Org. Chem.*, 2014, **79**, 5545–5557.
- N. K. Beyeh and R. Puttreddy, *Dalton Trans.*, 2015, **44**, 9881–9886.
- (a) N. K. Beyeh, A. Valkonen and K. Rissanen, *CrystEngComm*, 2014, **16**, 3758–3764; (b) K. Aoki, T. Nagae, R. Matsubara and I. Fujisawa, *Chem. Lett.*, 2004, **33**, 1264–1265; (c) I. Fujisawa, D. Takeuchi, R. Kato, K. Murayama and K. Aoki, *Bull. Chem. Soc. Jpn.*, 2011, **84**, 1133–1135; (d) K. Aoki, T. Nagae, S. Yamaguchi and I. Fujisawa, *Bull. Chem. Soc. Jpn.*, 2005, **78**, 2066–2068.
- (a) G. R. Desiraju, P. S. Ho, L. Kloo, A. C. Legon, R. Marquardt, P. Metrangolo, P. Politzer, G. Resnati and K. Rissanen, *Pure Appl. Chem.*, 2013, **85**, 1711; (b) P. Metrangolo, G. Resnati, T. Pilati and S. Biella, *Halogen Bonding: Fundamentals and Applications*, Springer, 2008; (c)





- R. Wilcken, M. O. Zimmermann, A. Lange, A. C. Joerger and F. M. Boeckler, *J. Med. Chem.*, 2013, **56**, 1363–1388; (d) K. Rissanen, *CrystEngComm*, 2008, **10**, 1107–1113; (e) C. B. Aakeröy, M. Baldrighi, J. Desper, P. Metrangolo and G. Resnati, *Chem. – Eur. J.*, 2013, **19**, 16240–16247; (f) F. Meyer and P. Dubois, *CrystEngComm*, 2013, **15**, 3058–3071; (g) R. W. Troff, T. Mäkelä, F. Topić, A. Valkonen, K. Raatikainen and K. Rissanen, *Eur. J. Org. Chem.*, 2013, **2013**, 1617–1637.
- 15 (a) M. T. Messina, P. Metrangolo, W. Panzeri, T. Pilati and G. Resnati, *Tetrahedron*, 2001, **57**, 8543–8550; (b) C. B. Aakeroy, T. K. Wijethunga, J. Benton and J. Desper, *Chem. Commun.*, 2015, **51**, 2425–2428; (c) C. B. Aakeroy, T. K. Wijethunga and J. Desper, *CrystEngComm*, 2014, **16**, 28–31.
- 16 (a) C. Janiak, *J. Chem. Soc., Dalton Trans.*, 2000, 3885–3896; (b) G. R. Desiraju, *Acc. Chem. Res.*, 2002, **35**, 565–573.
- 17 (a) M. Barceló-Oliver, A. Terrón, A. García-Raso, J. J. Fiol, E. Molins and C. Miravittles, *J. Inorg. Biochem.*, 2004, **98**, 1703–1711; (b) M. Livendahl, C. Goehry, F. Maseras and A. M. Echavarren, *Chem. Commun.*, 2014, **50**, 1533–1536; (c) M. G. D. Leed, N. Wolkow, D. M. Pham, C. L. Daniel, J. L. Dunaief and K. J. Franz, *J. Inorg. Biochem.*, 2011, **105**, 1161–1172; (d) M. Casimiro, L. Roces, S. García-Granda, M. J. Iglesias and F. López Ortiz, *Org. Lett.*, 2013, **15**, 2378–2381; (e) O. Knop, T. S. Cameron, P. K. Bakshi, A. Linden and S. P. Roe, *Can. J. Chem.*, 1994, **72**, 1870–1881; (f) M. N. Arshad, M. N. Tahir, I. U. Khan, W. A. Siddiqui and M. Shafiq, *Acta Crystallogr., Sect. E: Struct. Rep. Online*, 2009, **65**, o230; (g) D. Das and G. R. Desiraju, *Chem. – Asian J.*, 2006, **1**, 231–244; (h) S. Renganayaki, E. Subramanian, S. Shanmuga Sundara Raj and H.-K. Fun, *Acta Crystallogr., Sect. C: Cryst. Struct. Commun.*, 1999, **55**, 1525–1526; (i) J. Powell, A. Lough and T. Saeed, *J. Chem. Soc. Dalton Trans.*, 1997, 4137–4138; (j) R. Trokowski, S. Akine and T. Nabeshima, *Chem. – Eur. J.*, 2011, **17**, 14420–14428; (k) B. V. Meprathu, M. W. Justik and J. D. Protasiewicz, *Tetrahedron Lett.*, 2005, **46**, 5187–5190; (l) C. V. Ramana, Y. Goriya, K. A. Durugkar, S. Chatterjee, S. Krishnaswamy and R. G. Gonnade, *CrystEngComm*, 2013, **15**, 5283–5300; (m) B. K. Saha and A. Nangia, *Heteroat. Chem.*, 2007, **18**, 185–194; (n) Ö. Aydın, N. Çaylak Delibacs, H. Necefoglu and T. Hökelek, *Acta Crystallogr., Sect. E: Struct. Rep. Online*, 2012, **68**, m601–m602; (o) P. P. Kapadia, D. C. Swenson and F. C. Pigge, *Cryst. Growth Des.*, 2012, **12**, 698–706; (p) S. K. Nayak, M. K. Reddy, D. Chopra and T. N. Guru Row, *CrystEngComm*, 2012, **14**, 200–210; (q) M. Barceló-Oliver, A. García-Raso, A. Terrón, E. Molins, M. J. Prieto, V. Moreno, J. Martínez, V. Lladó, I. López, A. Gutiérrez and P. V. Escribá, *J. Inorg. Biochem.*, 2007, **101**, 649–659; (r) K. Goubitz, E. J. Sonneveld and H. Schenk, *Z. Kristallogr. - Cryst. Mater.*, 2001, **216**, 176.
- 18 C. R. Hubbard, V. L. Himes, A. D. Mighell and S. W. Page, *Acta Crystallogr., Sect. B: Struct. Crystallogr. Cryst. Chem.*, 1980, **36**, 2819–2821.

