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Sublimation of *p*-iso-propylcalix[4]arene under reduced pressure results in the concomitant formation of two new polymorphs (forms II<sub>P</sub> and III<sub>P</sub>). Both forms consist of interdigitated dimers of calixarene molecules, as does the known form I<sub>P</sub>. Despite similar inclusion behaviour to that of *p*-*tert*-butylcalix[4]arene, *p*-iso-propylcalix[4]arene does not appear to favour the formation of a transiently porous material.

## Introduction

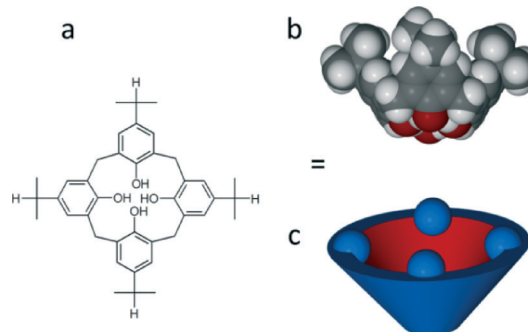
The extensive family of calix[*n*]arenes have a long history as host molecules in the field of inclusion chemistry.<sup>1</sup> For example, the cone-shaped *p*-*tert*-butylcalix[4]arene (*t*Bc) is well known for forming solvates with many different solvents. These solvates usually crystallise to adopt one of two types of host arrangements. One of these arrangements packs according to the space group *P4/n*, with a host:guest ratio of 1:1, while the other crystallises in *P4/nnc*, with a host:guest ratio of 2:1. Both of these packing modes can be described in terms of a bilayer arrangement of alternating up-down calixarene molecules with guest solvent molecules inserted into the host clefts. Two different guest-free forms of *t*Bc have been isolated using different methods of crystal growth. Ripmeester *et al.*<sup>2</sup> crystallised *t*Bc from heated tetradecane to produce the relatively close-packed (packing efficiency = 0.67) polymorph I<sub>B</sub>, in which the host molecules form mutually interdigitated dimers (*i.e.* one *tert*-butyl group of each molecule is inserted into the cavity of a facing host molecule). However, when *t*Bc is sublimed at 280 °C under dynamic vacuum the host molecules once again adopt a bilayer-type

## Concomitant polymorphs of *p*-iso-propylcalix[4]arene†

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arrangement with facing molecules slightly offset relative to one another (form II<sub>B</sub>). The cavities of two facing molecules from adjacent layers combine to produce discrete voids of approximately 235 Å<sup>3</sup> each, resulting in a relatively low packing efficiency of 0.59. At room temperature it is clear that all four *tert*-butyl groups of each calixarene are rotationally disordered whereas only one of the groups is disordered at 100 K. When form II<sub>B</sub> is heated to 130 °C it undergoes a minor and reversible phase change to a high temperature form (III<sub>B</sub>), which has a similar bilayer packing arrangement to that of form II<sub>B</sub>, except that adjacent bilayers become displaced laterally.<sup>3</sup> Despite its apparent lack of permanent channels between lattice voids, form II<sub>B</sub> possesses *transient porosity*, *i.e.* the crystals are able absorb a variety of solvents and gases into their discrete lattice voids, often in single-crystal to single-crystal (SC–SC) fashion. This was convincingly exemplified by a guest inclusion reaction involving the uptake of vinyl bromide with a concomitant SC–SC transformation of the host packing mode. Absorption of gases such as carbon dioxide, methane and acetylene does not result in rearrangement of the host molecules.<sup>3–5</sup>

The fascinating solid-state inclusion properties of *t*Bc prompted further studies aimed at tailoring the void space in



**Scheme 1** (a) The molecular structure of *p*-iso-propylcalix[4]arene (iPc), (b) iPc shown in space filling representation and (c) iPc shown as a cone (iso-propyl groups are shown as spheres lining the upper rim).

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apohost forms of close structural analogues. Some limited success was achieved by tetra-substitution of the *tert*-butyl groups with larger moieties such as *tert*-pentyl and *tert*-octyl groups. Although bilayer-type packing still occurred for the molecules with larger substituents, the more interesting guest-free offset face-to-face packing motif of II<sub>B</sub> was not observed for these systems. It therefore appears that the host packing arrangement observed for II<sub>B</sub> is highly sensitive to even slight addition of bulk to the upper rim of the calixarene.<sup>5,6</sup>

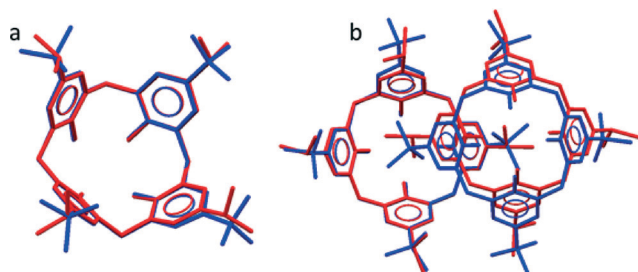
The present work was motivated by the observation (based on a search of the Cambridge Structural Database) that *p*-isopropylcalix[4]arene (**iPc**, Scheme 1) exhibits host packing arrangements with a variety of guests that are highly reminiscent of that of **tBc** with the same guests.<sup>7,8</sup> It was therefore hoped that, under the same crystal growth conditions, a slightly less bulky group on the upper rim would produce an apohost form that is isostructural to II<sub>B</sub>, but with slightly more void space.

A previously published apohost form of **iPc** (refcode YARYAR, here designated as form I<sub>P</sub>) crystallises as interdigitated dimers and the structure is analogous to that of I<sub>B</sub> (refcode QIGBEN).<sup>7</sup> An overlay of individual molecules of **tBc** and **iPc** shows that they adopt highly similar conformations, as expected (Fig. 1a). However, the degree of overlap between the dimers (Fig. 1b) of I<sub>B</sub> and I<sub>P</sub> is less precise, implying that the slightly different upper-rim moieties would significantly affect the overall extended periodicity of the two analogous structures relative to each other.

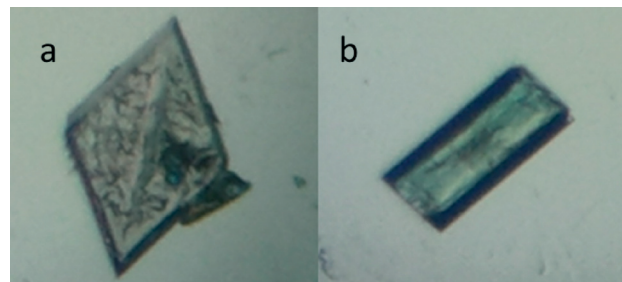
## Results and discussion

Perrin *et al.* had isolated apohost form I<sub>P</sub> from molten menthol at 65 °C.<sup>8</sup> Instead, inspired by our previous work on **tBc**, we sublimed the as-synthesised **iPc** (*i.e.* the **iPc**/toluene solvate) under dynamic vacuum at 260 °C. Sublimation growth resulted in the formation of crystals with two distinct morphologies (Fig. 2) and single-crystal X-ray diffraction analysis confirmed that these are indeed concomitant polymorphs (designated as forms II<sub>P</sub> and III<sub>P</sub>).

For comparison, selected unit cell parameters for forms I<sub>P</sub>, II<sub>P</sub>, III<sub>P</sub> and I<sub>B</sub> are reported in Table 1 (full crystallographic data provided in Table S1†). Forms II<sub>P</sub> and III<sub>P</sub> also crystallise



**Fig. 1** Structural overlays of **tBc** (blue) and **iPc** (red), (a) shows how closely the individual molecules of **iPc** and **tBc** overlap with each other while (b) shows the poor overlap between the dimers of **iPc** and **tBc**.



**Fig. 2** Photomicrographs of the new polymorphs of **iPc**: (a) form II<sub>P</sub> and (b) form III<sub>P</sub>.

as interdigitated dimers while the hoped-for non-interdigitated phase (*i.e.* analogous to II<sub>B</sub>) was not observed.

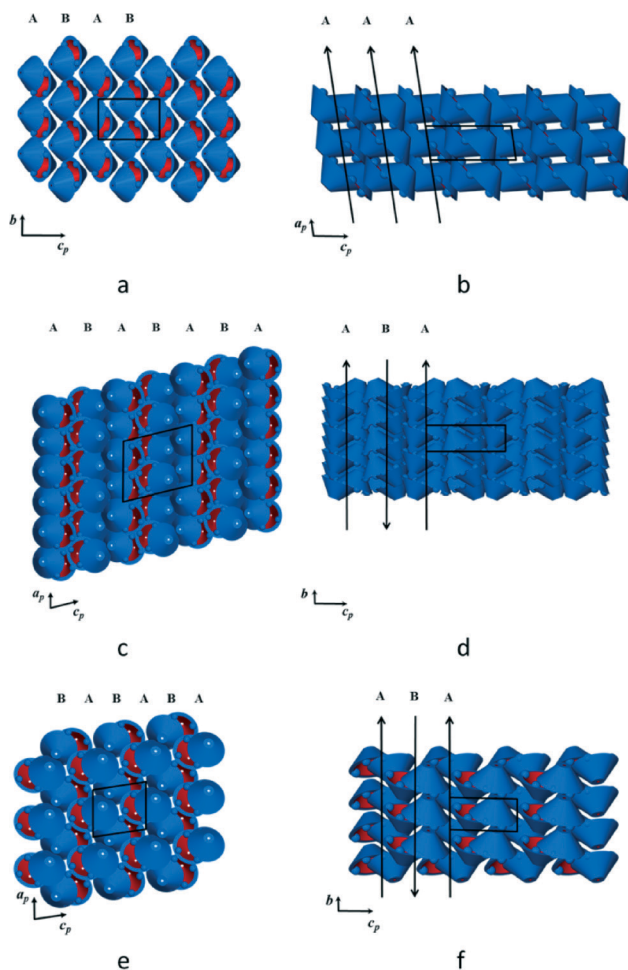
In the crystal structure of form I<sub>P</sub> the interdigitated dimers are stacked in columns parallel to [100]. In turn, these columns form layers parallel to (110) with alternating layers displaced laterally by 7.7 Å (Fig. 3a). The individual dimers (*i.e.* the mean plane through the eight iso-propyl groups) are inclined by approximately 32° relative to the *bc* plane and all the columns along *a* have the same orientation, as shown in Fig. 3b. In form II<sub>P</sub> the dimers are stacked in columns parallel to [010] (Fig. 3c), which are arranged in layers parallel to [110] that stack along *c*. Consecutive layers have anti-parallel molecular orientations and are displaced laterally by approximately 5.0 Å (Fig. 3d). The dimers are inclined by about 6° relative to the *ac* plane. In form III<sub>P</sub> the dimers also stack in columns parallel to [010], with layers parallel to [110] and stacked along *c* (Fig. 3e). Alternate layers are displaced laterally by approximately 8.8 Å, with consecutive layers having an anti-parallel arrangement (Fig. 3f) and a molecular inclination angle of about 23° relative to the *ac* plane. It is noteworthy that the calculated densities of I<sub>P</sub>, II<sub>P</sub> and III<sub>P</sub> differ by less than 1%.

Hirshfeld surface analysis of the **iPc** polymorphs and of form I<sub>B</sub> of **tBc** was carried out using the program CrystalExplorer.<sup>9</sup> The Hirshfeld surfaces were mapped using  $d_{\text{norm}}$ , which is a normalised contact that takes into account the van der Waals radius of each atom. Although the 2D fingerprint plots for the form I<sub>B</sub> apohost and the three polymorphs of **iPc** are quite different, they show strikingly similar features (Fig. 4a–d). The **iPc** polymorphs and form I<sub>B</sub> experience multiple C–H⋯π interactions, as evidenced by the ‘saw-tooth’ shapes on either side of the diagonal  $d_e = d_i$  (Fig. 4e–h).

**Table 1** Selected unit cell parameters of **tBc** and the polymorphs for **iPc**

	I <sub>P</sub>	II <sub>P</sub>	III <sub>P</sub>	I <sub>B</sub>
Space group	<i>P2</i> <sub>1</sub> / <i>c</i>	<i>C2/c</i>	<i>P2</i> <sub>1</sub> / <i>n</i>	<i>P2</i> <sub>1</sub> / <i>c</i>
<i>a</i> (Å)	9.432(1)	24.851(3)	17.681(1)	9.5878
<i>b</i> (Å)	15.349(2)	9.412(1)	9.525(1)	30.5003
<i>c</i> (Å)	23.578(3)	29.214(4)	19.984(2)	13.5412
β (°)	98.751(2)	103.211(2)	98.363(2)	109.852
<i>D</i> <sub>calc</sub> (g cm <sup>-3</sup> )	1.167	1.182	1.184	1.47
Temp. (K)	100	100	100	173

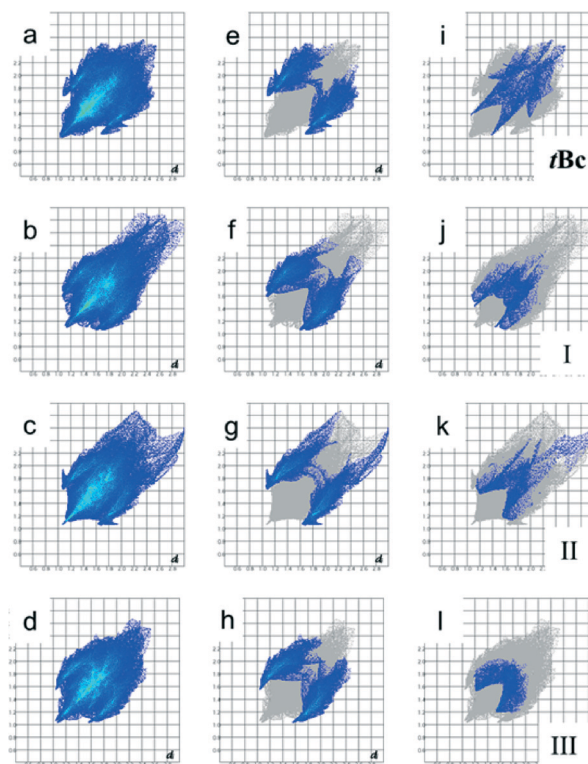




**Fig. 3** Schematic representations of the packing arrangements of forms  $I_p$ ,  $II_p$  and  $III_p$  with individual molecules shown as cones. Consecutive layers of forms  $I_p$ ,  $II_p$  and  $III_p$  are laterally displaced as shown in (a), (c) and (e), respectively. Consecutive columns in  $I_p$  are oriented parallel to one another (b) while in forms  $II_p$  (d) and  $III_p$  (f) the columns are anti-parallel.

These interactions result from the insertion of a single *tert*-butyl or iso-propyl moiety into its partner's cavity by the two calixarenes comprising a dimer.

The C–H $\cdots\pi$  interactions for form  $I_B$  contribute 20.3% to the total area of the Hirshfeld surface while those of the **iPc** polymorphs contribute 23.4%, 24.1% and 23.2% for forms  $I_p$ ,  $II_p$  and  $III_p$ , respectively. The O $\cdots$ H(O) interactions, shown as short broad spikes directed towards the lower left corner of each plot, are due to the intramolecular hydrogen bonded ring formed by the hydroxyl groups on the lower rim of each calixarene (Fig. 4i–l). Interestingly, form  $I_B$  also experiences weak O $\cdots$ H(C) interactions that are not present in the fingerprint plots of the **iPc** polymorphs – these result from interactions between hydrogen atoms belonging to *tert*-butyl moieties and the hydroxyl groups of neighbouring calixarenes. The total contributions of the O $\cdots$ H(O) (as well as O $\cdots$ H(C) interactions for form  $I_B$ ) to the Hirshfeld surfaces are 5.9, 6.3, 6.0 and 6.2% for forms  $I_B$ ,  $I_p$ ,  $II_p$  and  $III_p$ , respectively.



**Fig. 4** Fingerprint plots for  $I_B$ ,  $I_p$ ,  $II_p$  and  $III_p$ . The left-hand column shows the complete fingerprint plots, the middle column shows only the C–H $\cdots\pi$  interactions and the column on the right shows both the O $\cdots$ H(O) and O $\cdots$ H(C) interactions.

Melting temperatures and enthalpies ( $T_{on}$ ,  $T_{peak}$ ,  $\Delta H_{fus}$  and  $\Delta H_{des}$ ) were determined for the three polymorphs of **iPc** and **iPc**·toluene using differential scanning calorimetry (DSC) and these values are reported in Table 2. DSC thermograms for the phases  $I_p$ ,  $II_p$  and  $III_p$  are shown in Fig. 5; each thermogram displays a single thermal event corresponding to the melt endotherm of each phase.

The **iPc**·toluene solvate (Fig. S1†) undergoes two thermal events that are related to desolvation and subsequent melting of the apohost. The observed melting point of the desolvated material corresponds to the melting point of form  $I_p$  (Table 2). From the thermal data for the three apohost forms of **iPc** it appears that the highest melting phase (form  $I_p$ ) also has the highest heat of fusion. Indeed, the heats of fusion can be arranged in the order  $\Delta H_{fusI} > \Delta H_{fusII} > \Delta H_{fusIII}$ .

**Table 2** Thermoanalytical results for the different phases of **iPc** as determined from DSC measurements (an average of two measurements in each case)

Phase	$T_{on}$ (°C)	$T_{peak}$ (°C)	$\Delta H_{fus}$ (J g $^{-1}$ )	$\Delta H_{des}$ (J g $^{-1}$ )
Desolvation	133.1	159.3	—	53.4
Melt	293.5	295.2	76.4	—
$I_p$	294.3	296.1	75.3	—
$II_p$	289.9	292.4	62.1	—
$III_p$	277.3	284.8	37.1	—





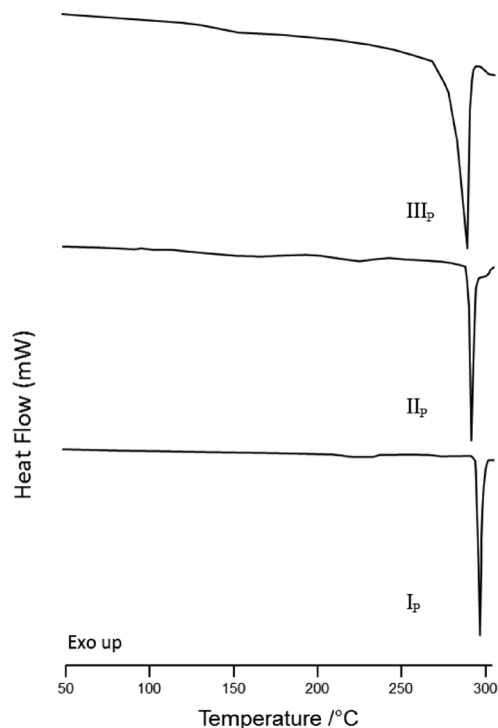


Fig. 5 DSC traces of forms I<sub>P</sub> (bottom), II<sub>P</sub> (middle) and III<sub>P</sub> (top) heated at 10 K min<sup>-1</sup> in the range 25 to 315 °C.

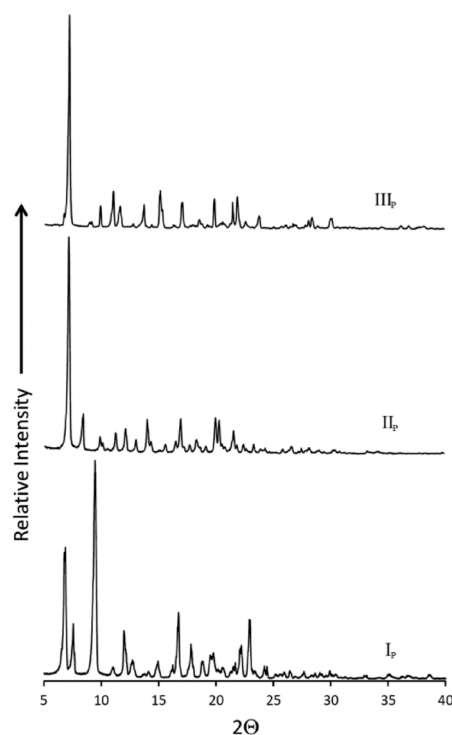


Fig. 6 Experimental powder X-ray diffraction patterns of forms I<sub>P</sub> (bottom), II<sub>P</sub> (middle) and III<sub>P</sub> (top).

Furthermore, we believe that the higher melting phase I<sub>P</sub> is also the thermodynamically most stable of the three forms since it can be crystallized from a saturated solution. According to the heat of fusion rule proposed by Burger *et al.* the three forms are monotropes (or monotropically related to one another).<sup>10</sup>

In order to understand the relationships between forms I<sub>P</sub>, II<sub>P</sub> and III<sub>P</sub>, temperature-cycled DSC (TC-DSC) experiments were carried out by heating each sample in the range 25 to 315 °C, followed by cooling to 25 °C and then reheating to 315 °C. The TC-DSC experiments were carried out at different heating rates, ranging from 10 to 20 K min<sup>-1</sup> at 5 K min<sup>-1</sup> increments (Fig. S2†). Since the toluene solvate was used to generate the new phases II<sub>P</sub> and III<sub>P</sub> in the sublimation experiment, it was also used as the starting phase for the TC-DSC experiments. The first TC-DSC experiment, which was carried out at a scanning rate of 10 K min<sup>-1</sup> resulted in form III<sub>P</sub>, while a scanning rate of 15 K min<sup>-1</sup> yielded a mixture of phases II<sub>P</sub> and III<sub>P</sub>. From the ratio of the corresponding enthalpies we determined that more of form III<sub>P</sub> was produced than of form II<sub>P</sub> (Fig. S3†). A rate of 20 K min<sup>-1</sup> also resulted in a mixture of forms II<sub>P</sub> and III<sub>P</sub>, but in this case the ratios were more evenly distributed. Powder X-ray diffraction (PXRD) was used to characterise the pure phases (Fig. 6) and also to confirm the identity of the phases obtained from DSC (calculated PXRD profiles Fig. S4†). The TC-DSC experiments imply that the cooling rate influences which phases are produced, and that forms II<sub>P</sub> and III<sub>P</sub> are kinetic products, whereas I<sub>P</sub> is the thermodynamic product.

## Conclusions

We have described the concomitant isolation and characterisation of two new polymorphs (II<sub>P</sub> and III<sub>P</sub>) of **iPc** grown by sublimation. Similar to the known form I<sub>P</sub>, the two new forms consist of interdigitated calixarene dimers. Thermoanalytical measurements of all three forms imply that none of them interconvert to one another prior to their melting. Moreover, the higher melting form I<sub>P</sub> has the highest enthalpy of fusion and is most likely the thermodynamically stable form since it can be crystallised from solution. Forms II<sub>P</sub> and III<sub>P</sub> appear to be kinetic forms since they can be isolated upon rapid cooling of the melt. We conclude that forms I<sub>P</sub>, II<sub>P</sub> and III<sub>P</sub> are monotropes while II<sub>P</sub> and III<sub>P</sub> can more specifically be considered *kinetic* monotropes of form I<sub>P</sub>. A temperature gradient within the glass oven used for the sublimation experiments could explain the origin of the concomitant forms since II<sub>P</sub> and III<sub>P</sub> can be generated based on different cooling rates that only differ marginally.

The original objective of this work was to establish whether **iPc** could fully mimic the highly interesting transient porosity of **tBc**. Unfortunately **iPc** does not appear to form an apohost form that is analogous to II<sub>B</sub>. Although only one interdigitated form of pure **tBc** apohost is known (form I<sub>B</sub>), **iPc** yields three such forms as monotropic polymorphs of one another. This study demonstrates that, despite several marked similarities in their inclusion behaviour, **tBc** and **iPc** show very different packing trends in the manifestations of their apohost forms.



## Acknowledgements

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