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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_p and III_p). Both forms consist of interdigitated dimers of calixarene molecules, as does the known form I_p. 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

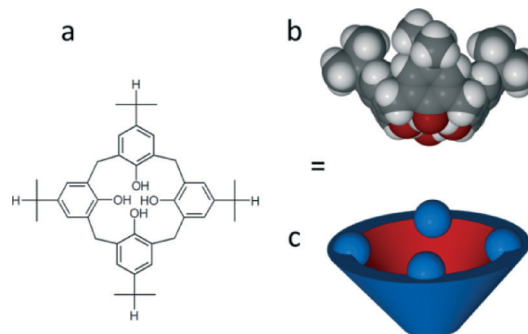
The extensive family of calix[*n*]arenes have a long history as host molecules in the field of inclusion chemistry.¹ For example, the cone-shaped *p*-*tert*-butylcalix[4]arene (*t*Bc) is well known for forming solvates with many different solvents. These solvates usually crystallise to adopt one of two 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.*² crystallised *t*Bc from heated tetradecane to produce the relatively close-packed (packing efficiency = 0.67) polymorph I_B, 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_B). The cavities of two facing molecules from adjacent layers combine to produce discrete voids of approximately 235 Å³ 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_B is heated to 130 °C it undergoes a minor and reversible phase change to a high temperature form (III_B), which has a similar bilayer packing arrangement to that of form II_B, except that adjacent bilayers become displaced laterally.³ Despite its apparent lack of permanent channels between lattice voids, form II_B 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.^{3–5}

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_B was not observed for these systems. It therefore appears that the host packing arrangement observed for II_B is highly sensitive to even slight addition of bulk to the upper rim of the calixarene.^{5,6}

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.^{7,8} 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_B, but with slightly more void space.

A previously published apohost form of iPc (refcode YARYAR, here designated as form I_P) crystallises as interdigitated dimers and the structure is analogous to that of I_B (refcode QIGBEN).⁷ 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_B and I_P 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_P from molten menthol at 65 °C.⁸ 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_P and III_P).

For comparison, selected unit cell parameters for forms I_P, II_P, III_P and I_B are reported in Table 1 (full crystallographic data provided in Table S1†). Forms II_P and III_P also crystallise

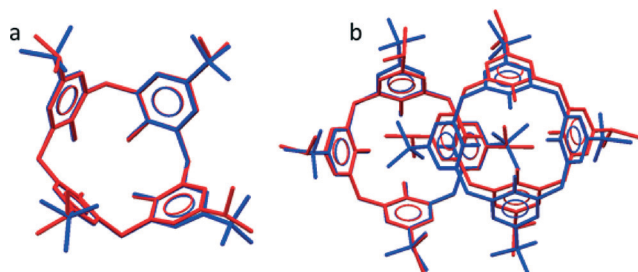


Fig. 1 Structural overlays of tBc (blue) and iPc (red), (a) shows how closely the individual molecules of iPc and tBc overlap with each other while (b) shows the poor overlap between the dimers of iPc and tBc.



Fig. 2 Photomicrographs of the new polymorphs of iPc: (a) form II_P and (b) form III_P.

as interdigitated dimers while the hoped-for non-interdigitated phase (*i.e.* analogous to II_B) was not observed.

In the crystal structure of form I_P 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_P 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_P 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_P, II_P and III_P differ by less than 1%.

Hirshfeld surface analysis of the iPc polymorphs and of form I_B of tBc was carried out using the program CrystalExplorer.⁹ The Hirshfeld surfaces were mapped using d_{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_B apohost and the three polymorphs of iPc are quite different, they show strikingly similar features (Fig. 4a–d). The iPc polymorphs and form I_B 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 _P	II _P	III _P	I _B
Space group	<i>P</i> 2 ₁ / <i>c</i>	<i>C</i> 2/ <i>c</i>	<i>P</i> 2 ₁ / <i>n</i>	<i>P</i> 2 ₁ / <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> _{calc} (g cm ^{−3})	1.167	1.182	1.184	1.47
Temp. (K)	100	100	100	173



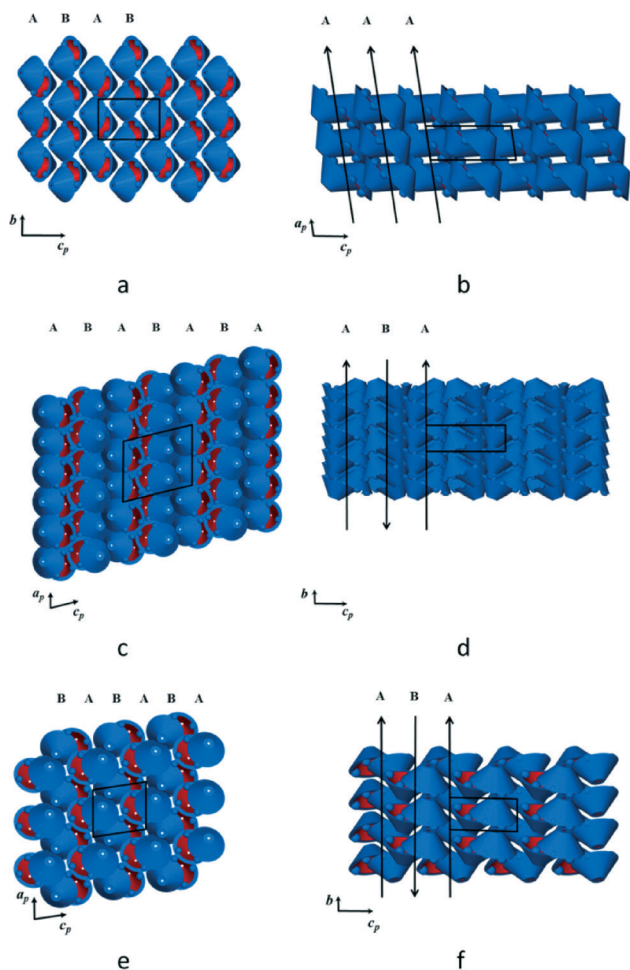


Fig. 3 Schematic representations of the packing arrangements of forms I_P , II_P and III_P with individual molecules shown as cones. Consecutive layers of forms I_P , II_P and III_P are laterally displaced as shown in (a), (c) and (e), respectively. Consecutive columns in I_P are oriented parallel to 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.

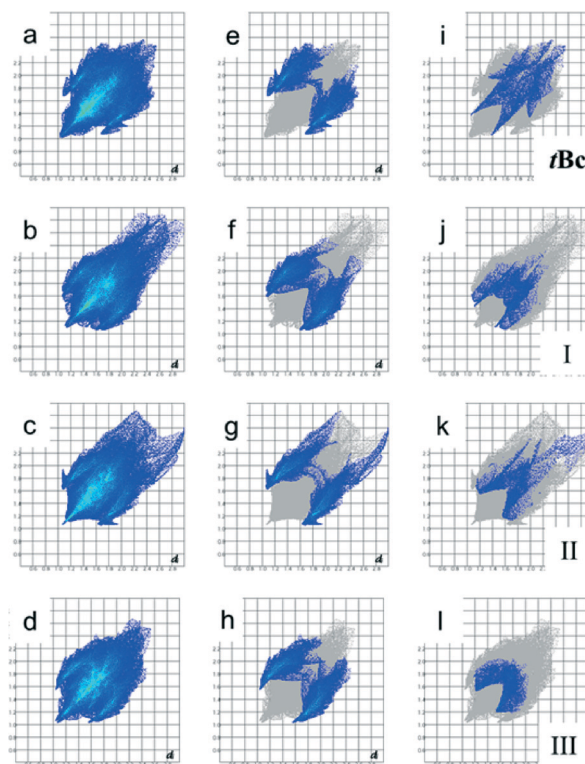


Fig. 4 Fingerprint plots for I_B , I_P , II_P and III_P . The left-hand column shows the complete fingerprint plots, the middle column shows only the C–H $\cdots\pi$ interactions and the column on the right shows both the O $\cdots$ H(O) and O $\cdots$ H(C) interactions.

Melting temperatures and enthalpies (T_{on} , T_{peak} , ΔH_{fus} and ΔH_{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)	ΔH_{fus} (J g ^{−1})	ΔH_{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_P (bottom), II_P (middle) and III_P (top) heated at 10 K min^{-1} in the range 25 to $315\text{ }^{\circ}\text{C}$.

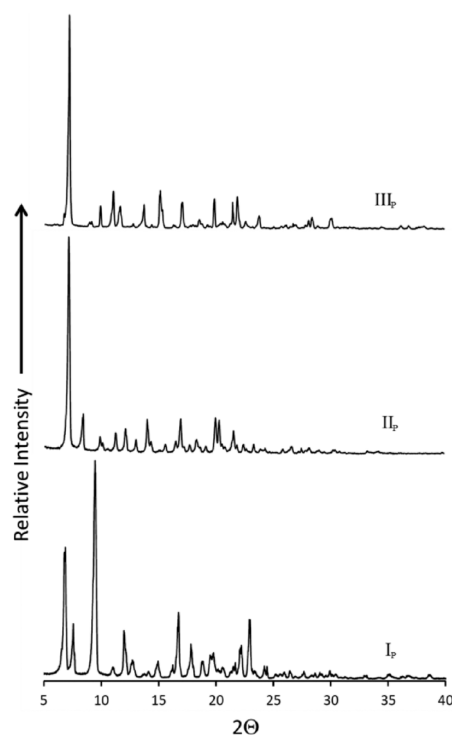


Fig. 6 Experimental powder X-ray diffraction patterns of forms I_P (bottom), II_P (middle) and III_P (top).

Furthermore, we believe that the higher melting phase I_P 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).¹⁰

In order to understand the relationships between forms I_P , II_P and III_P , temperature-cycled DSC (TC-DSC) experiments were carried out by heating each sample in the range 25 to $315\text{ }^{\circ}\text{C}$, followed by cooling to $25\text{ }^{\circ}\text{C}$ and then reheating to $315\text{ }^{\circ}\text{C}$. The TC-DSC experiments were carried out at different heating rates, ranging from 10 to 20 K min^{-1} at 5 K min^{-1} increments (Fig. S2†). Since the toluene solvate was used to generate the new phases II_P and III_P 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^{-1} resulted in form III_P , while a scanning rate of 15 K min^{-1} yielded a mixture of phases II_P and III_P . From the ratio of the corresponding enthalpies we determined that more of form III_P was produced than of form II_P (Fig. S3†). A rate of 20 K min^{-1} also resulted in a mixture of forms II_P and III_P , 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_P and III_P are kinetic products, whereas I_P is the thermodynamic product.

Conclusions

We have described the concomitant isolation and characterisation of two new polymorphs (II_P and III_P) of **iPc** grown by sublimation. Similar to the known form I_P , 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_P has the highest enthalpy of fusion and is most likely the thermodynamically stable form since it can be crystallised from solution. Forms II_P and III_P appear to be kinetic forms since they can be isolated upon rapid cooling of the melt. We conclude that forms I_P , II_P and III_P are monotropes while II_P and III_P can more specifically be considered *kinetic* monotropes of form I_P . A temperature gradient within the glass oven used for the sublimation experiments could explain the origin of the concomitant forms since II_P and III_P 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_B . Although only one interdigitated form of pure **tBc** apohost is known (form I_B), **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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