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Review Article

t-Butylcalix[4]arene Host–Guest Compounds: Structure and Dynamics**

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Abstract. Despite the proliferation of structural studies on calixarene host–guest compounds, some important structural details remain obscure. In particular, the ubiquitous disorder of the calix *t*-butyl group often hinders a detailed determination of the non-bonding interactions between host and guest. We propose and develop a synoptic approach in which several complementary characterization techniques (X-ray diffraction and NMR) provide a powerful means of assessing the interplay of structure and dynamics in calixarene-guest compounds. The simple *t*-butylcalix[4]arene-guest compounds (guest = toluene, nitrobenzene, cyclohexane, *n*-pentane, 1-chlorobutane) are examined with this approach, and new structural and dynamic features are uncovered.

Key words: Calixarene, inclusion, structure, NMR, dynamics.

1. Introduction

In structural investigations of calixarene host–guest inclusion compounds, X-ray diffraction (XRD) has played a primary role [1]. Solid-state magnetic resonance studies, specifically nuclear magnetic resonance (NMR), have to a lesser extent provided a means to characterize and elucidate the structure of calixarene compounds [2–4]. In this work we develop a *synoptic* approach to the structure and dynamics of *t*-butylcalix[4]arene (C4A) compounds in which both XRD and NMR techniques are used in a complementary fashion. XRD, with its sensitivity to long-range ordering, and NMR spectroscopy as a probe of local or short-range ordering, combine to give a comprehensive structural picture unattainable from either technique alone.

   Present interest in calixarene chemistry was sparked by the XRD study of the C4A–toluene compound by Andreetti in 1979 [5]. The structural model developed
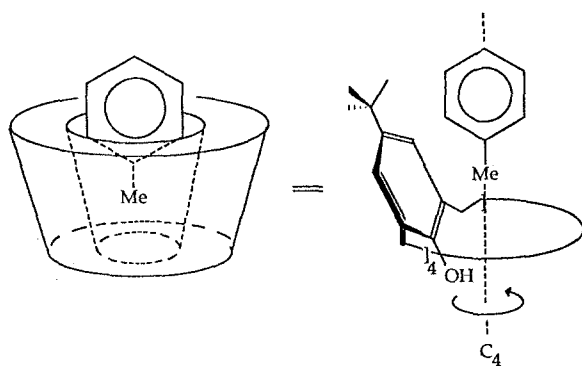
Figure 1. *t*-Butylcalix[4]arene–toluene.

showed that toluene is inserted methyl-first into the calixarene cavity with its long molecular axis aligned with the calixarene 4-fold symmetry axis (Figure 1), and is disordered about this axis over two positions perpendicular to each other. In this model, the calixarene *t*-butyl groups occupy two sites related by rotation in a 77 : 23 ratio; this ratio is puzzling, and it is difficult to relate this disorder to specific non-bonding interactions between toluene and the calixarene. Many calixarene publications acknowledge the difficulties arising from disordered *t*-butyl groups in this and other calixarene structures, as *t*-butyl group disorder is widespread and not well understood [1, 6–10]. Lack of understanding of the host–guest structural behavior, specifically the disorder in the host *t*-butyl groups and the guest, is reflected in the moderate to high R values typical of calixarene inclusion compounds (Table I).

Modelling of host-guest interactions in calixarene compounds [10, 29–31] is restricted by the quality of the structural information. To understand and to predict behaviour in calixarene (and in general, supramolecular) chemistry by linking structure to function necessitates accurate structural data.

This paper presents a more accurate structural model of the first structurally-characterized calixarene compound, C4A-toluene, compiled from the complementary techniques of XRD and NMR. The synoptic approach is further developed with C4A-nitrobenzene, in which the guest induces asymmetry in the calixarene host, and C4A-aliphatic inclusion compounds which address the role π-methyl interactions play in the stability of calixarene compounds.

2. *t*-Butylcalix[4]arene–Toluene

C4A–toluene poses an interesting question: why would toluene, with no more than 2-fold symmetry, induce 4-fold symmetry in the host lattice? If the disorder is static, one might expect the 4-fold symmetry to be achieved by space-averaging of individual host–guest units of lower symmetry. On the other hand, if the disorder is

Table I. XRD structural studies of cone-shaped t-butylcalix[n]arene compounds.

Host	Guest	R value	Ref
t-Bucalix[4]arene	toluene	0.092	6
t-Bucalix[4]arene	anisole	0.073	7*
Cs[t-Bucalix[4]arene]	Cs^+, acetonitrile	0.048	8
NEt_4[t-Bucalix[4]arene]	CH_3CN, H_2O	0.083	9*
t-Bucalix[4]arene, crown-bridged	pyridine	0.12	10
t-Bucalix[4]arene tetracarbonate	acetonitrile	0.075	11
t-Bucalix[4]arene tetramethoxy	toluene, Na^+	0.090	12
t-Bucalix[4]arene diquinone	Na^+	0.090	13
t-Bucalix[4]arene, Ti	toluene	0.067	14
t-Bucalix[4]arene, Fe	NH_3, n-hexane	0.083	14
t-Bucalix[4]arene, Co_3	toluene, thf	0.14	14
1,3-diMeO-t-Bucalix[4]arene, crown-5	empty	0.14	15
1,3-diEtO-t-Bucalix[4]arene, crown-5	K^+	0.107	15
t-Bucalix[4]arene, picric-, K^+	CH_2Cl_2	0.106	16
t-Bucalix[4]arene tetramethoxy, m-terphenyl	empty	0.120	16
Li[t-Bucalix[4]areneP(H)NMe$_2$]	THF	0.072	17*
t-Bucalix[4]arene, 2-pyridylmethyloxy	ethanol	0.074	18
[Ir(η^5-C$_5$Me$_5$)$_2$(η^6:η^6t-Bucalix[4]arene)][BF$_4$]$_3$	CH_3NO_2, ether	0.057	19*
t-Bucalix[4]arene, tetraamide	KCSN, CH_3OH	0.113	20
t-Bucalix[4]arene, tetraamide	KI, CH_3OH	0.158	20
t-Bucalix[5]arene	tetralin, 2EtOH	0.081	21
t-Bucalix[6]arene	benzene	0.12	22
t-Bucalix[6]arene	acetonitrile	0.113	23
t-Bucalix[6]arene	empty	high	24
t-Bucalix[6]arene, Ti	toluene	0.094	25
t-Bucalix[8]arene	pyridine	0.169	26
t-Bucalix[8]arene, octaacetoxy	empty	0.087	27
t-Bucalix[8]arene	C_{60}	–	28

*No t-butyl disorder reported.

dynamic, the high symmetry can be achieved by time averaging of lower symmetry guest–host configurations.

The 290 K ^{13}C CP-MAS NMR spectrum of C4A-toluene is consistent with 4-fold symmetric host–guest units (Figure 2a). Furthermore, the ^{2}H NMR spectrum of C4A–toluene-d_8 reveals that the guest undergoes axial rotation close to the fast motion limit (10^8 Hz) at room temperature. Thus the guest disorder must be dynamic. Additional information comes from calorimetry, which shows that as the temperature is lowered, the crystal experiences a thermal event at 248 K [4]. Clearly, as the guest motion is slowed, a phase transition to a lower symmetry crystal occurs. We were quite confident, then, that a low temperature (< 248 K)
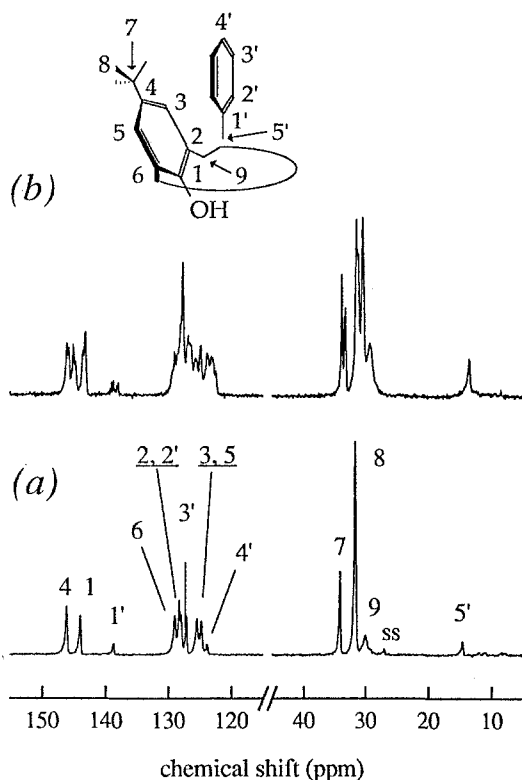
Figure 2. 50.3 MHz ^{13}C CP-MAS NMR spectra of C4A–toluene: (a) 290 K; (b) 115 K. SS indicates a spinning sideband.

XRD crystal structure determination would show a structure with less than 4-fold symmetry.

Surprisingly, the 150 K structure refined to the same $P4/n$ structure as initially reported at room temperature: there was no evidence of any phase change! Additional ^{13}C and ^{2}H NMR studies were then carried out. The ^{13}C CP-MAS NMR spectrum at 115 K shows a significant increase in multiplicity of the carbon resonances and suggests a lowered host–guest symmetry (Figure 2b). Furthermore, the ^{2}H NMR spectra of C4A–toluene-d_5 show clearly that between 129 and 179 K the guest behaves as a 2-fold rotor with rotation occurring about the long molecular axis (Figure 3a). Both spectra, and particularly the latter, indicate that though the lattice symmetry from diffraction may be 4-fold, individual C4A–toluene units possess 2-fold symmetry. In other words, at 150 K, the high apparent symmetry is attained by space averaging.

The 150 K XRD data were then refined with 2-fold local symmetry of the calix–guest units. The t-butyl disordering, previously 77:23, now becomes 50:50 due to the superpositioning of two elliptical 2-fold symmetric calix cavities; the disorder
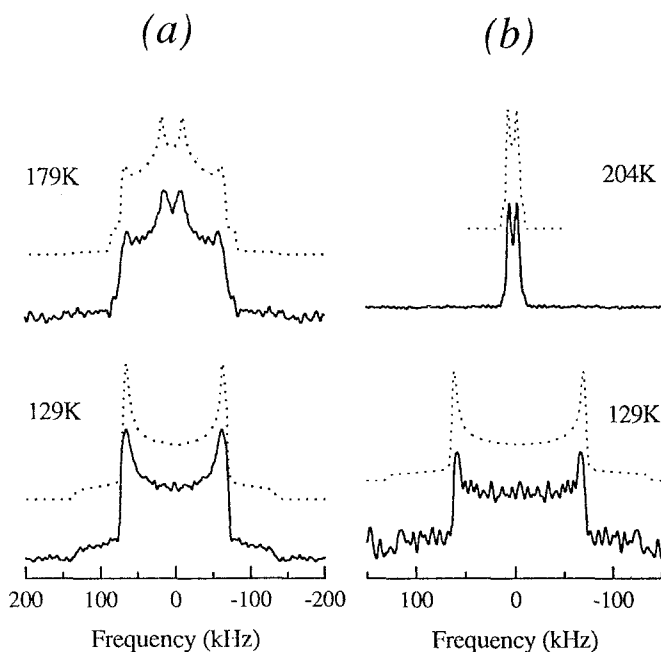
Figure 3. Observed and calculated (dashed) 30.7 MHz ^{2}H NMR spectra of (a) C4A–toluene-d_5 and (b) *t*-butyl-d_9-calix[4]arene–toluene at indicated temperatures.

is seen to involve translation of one end of the calix aromatic rings (Figure 4). The two *t*-butylphenol positions are related to each other by translation and a rotation.

Variable temperature ^{2}H NMR spectra of *t*-butyl-d_9-calix[4]arene–toluene are consistent with C_3 (methyl) and C_3' (*t*-butyl) rotation. The C_3, C_3' fast motion limit lineshape is narrower than expected, and one motion that may account for this is reorientation of the *t*-butyl group between the two disordered positions observed with the XRD model (Figure 3b). The ^{2}H NMR data give an angular difference between the two positions of $\theta = 15.4°$ whereas $\theta = 9.5°$ from XRD. In summary, the *t*-butyl disorder, like the toluene disorder, is dynamic.

The ^{2}H lineshapes between 129 and 179 K can be simulated as a function of the jump rate k [32]. An Arrhenius plot of ln k vs $1/T$ gives a slope from which a barrier to 2-fold toluene rotation can be derived: $E_{act} = 34.0$ (3.1) kJ mol^{-1}.

Refinement of the guest position at 150 K indicated that roughly 10% of the toluene is inverted, i.e., the methyl group is sticking out of the cavity. A careful re-determination of the ^{13}C CP-MAS NMR spectrum showed methyl carbon intensities at both δ 15.0 and 21.9 ppm. The former corresponds to the 'methyl-in' toluene and has an integrated intensity of 0.95 whereas the latter is the 'methyl-out' signal with intensity 0.05.

Additional insight concerning the guest position comes from both XRD and ^{2}H NMR. Foreshortening of guest C—C bond distances lying off the crystallographic
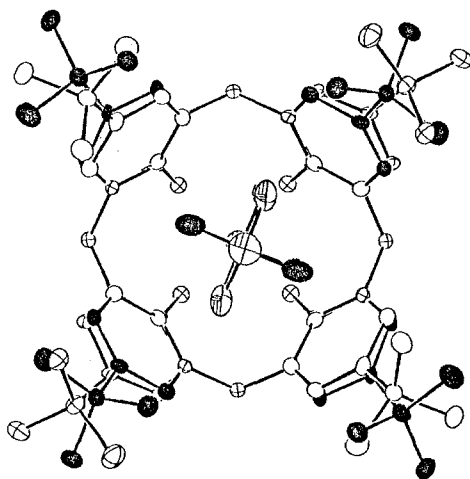
Figure 4. Structure of C4A–toluene host–guest unit showing the two elliptical calix cavities (looking in the *ab* plane). The 50:50 disorder of the *t*-butyl groups and the toluene guest is illustrated by atoms open or filled.

4-fold axis suggests that the toluene is tilted from the calix C_4 axis by $7°$. As the toluene *para*-CD bond lies along the rotation axis, the effective quadrupolar coupling constant, χ, will keep its static value only if the toluene is a pure axial rotor. Narrowing of the *para*-deuteron line upon increase in temperature ($\chi_{179} = 173.33$ kHz; $\chi_{129} = 178.67$ kHz) is consistent with the toluene tilted from the calix 4-fold axis by $8°$.

The dynamic picture of the C4A–toluene compound at room temperature that emerges is one in which the guest and host, both in dynamic states, interact, possibly in a correlated fashion: a dynamic toluene carves out an anisotropic volume of occupation and induces 2-fold symmetry in the flexible calix framework. In addition to this correlation between guest and host, correlation between the host and a neighbouring host is also possible. Local dynamics extend throughout the crystal lattice, presumably through correlated dynamics. Upon a temperature quench (290 to 150 K), correlated guest–host and host–host orientations are frozen in, as evidenced by the observation of weak reflection peaks at half-integer h and k, which suggest an amalgamation of some calix–guest units into a superstructure, and by increased multiplicity in the ^{13}C NMR resonances, which suggests a lack of correlation in 2-fold distortion of adjacent guest–host units.

3. *t*-Butylcalix[4]arene–Nitrobenzene (C4A-NB): A Distorted Host

Toluene is a guest that induces calix host distortions on a fast timescale (10^8 Hz) at room temperature. Is it possible to find a guest that distorts the host in a more drastic and thus permanent fashion? C4A compounds with over 30 different guests

were screened by ^{13}C CP-MAS NMR spectroscopy to see if such a guest existed. Three host-distorting guests were identified: nitrobenzene (NB), and 3- and 4-nitrotoluene [33]. All three C4A compounds give ^{13}C CP-MAS NMR spectra with varying degrees of multiplicity and, by extension, symmetry. The guest generating the lowest symmetry C4A structure was nitrobenzene (Figure 5).

In contrast to toluene in C4A–toluene, nitrobenzene sits in the calix cavity without its long molecular axis being in alignment with the calix axis (the angle between the two is 68°). The nitro group protrudes from the cavity, and most likely accounts for the distorted host, in which none of the four calix *t*-butylphenol subunits are symmetry-related. The nitro group sits between two *t*-butylphenol subunits that are positionally ordered on account of minimal dynamic host–guest interactions. Whereas the C4A-NB *a* and *b* lattice parameters are close to those of C4A–toluene, the *c*-axis is doubled as a result of the packing of *ab* planes being disrupted by the guest (Table II).

The variable temperature ^{2}H NMR spectra of C4A–NB-d_5 (200–290 K) reveal that the guest undergoes 2-fold flips like the guest in C4A–toluene at low temperature. The barrier to 2-fold rotation derived from the Arrhenius plot (E_{act} = 56.6 (1.3) kJ mol^{-1}) is significantly higher than the toluene 2-fold flip barrier (E_{act} = 34.0 (3.1) kJ mol^{-1}) due, in part, to the inability of the host to match the guest molecular symmetry as well as differences in crystalline packing densities.

Unlike most C4A–guest compounds, C4A–NB crystallizes in a non-centrosymmetric space group ($Pc2_1n$). As nitrobenzene is a polar molecule (μ = 3.93 D), its dipole is aligned in the crystal lattice such that all the molecular dipoles along the *b*-axis will be additive. The net alignment of dipoles is a major requirement for nonlinear optical (NLO) materials [34]. In C4A–NB, the fraction of molecular dipole per unit mass (0.16) is significantly higher than in other NLO inclusion compounds and doped polymers [34,35]. The structural similarities between nitrobenzene and the NLO molecules 4-nitroaniline and 2-methyl-4-nitroaniline suggest C4A inclusion compounds of these guests may be significant candidates for NLO materials.

4. *t*-Butylcalix[4]arene-Hydrocarbon Compounds

One nonbonding interaction often invoked to explain the stability of calixarene host–guest compounds is that between the host *t*-butyl groups and the guest aromatic ring [1, 10], and is based on XRD studies on several compounds [5, 10]. *t*-Butyl groups are significant as the related calix[4]arene (without *t*-butyl groups) is a poor host for guest inclusion [36]. In an early modelling paper, a gap between the observed and calculated guest angular potential in a 1:1 crown-bridged-C4A–pyridine compound was attributed to stabilizing π_{guest}–Me$_{host}$ interactions [10]. In subsequent structural work, the stability of calix compounds is attributed to π-methyl interactions [1,5,7,10], including the *t*-butylcalix[8]arene–fullerene compounds [37]. Understanding the role of this interaction is hindered by the lack of accurate structural models (see above).
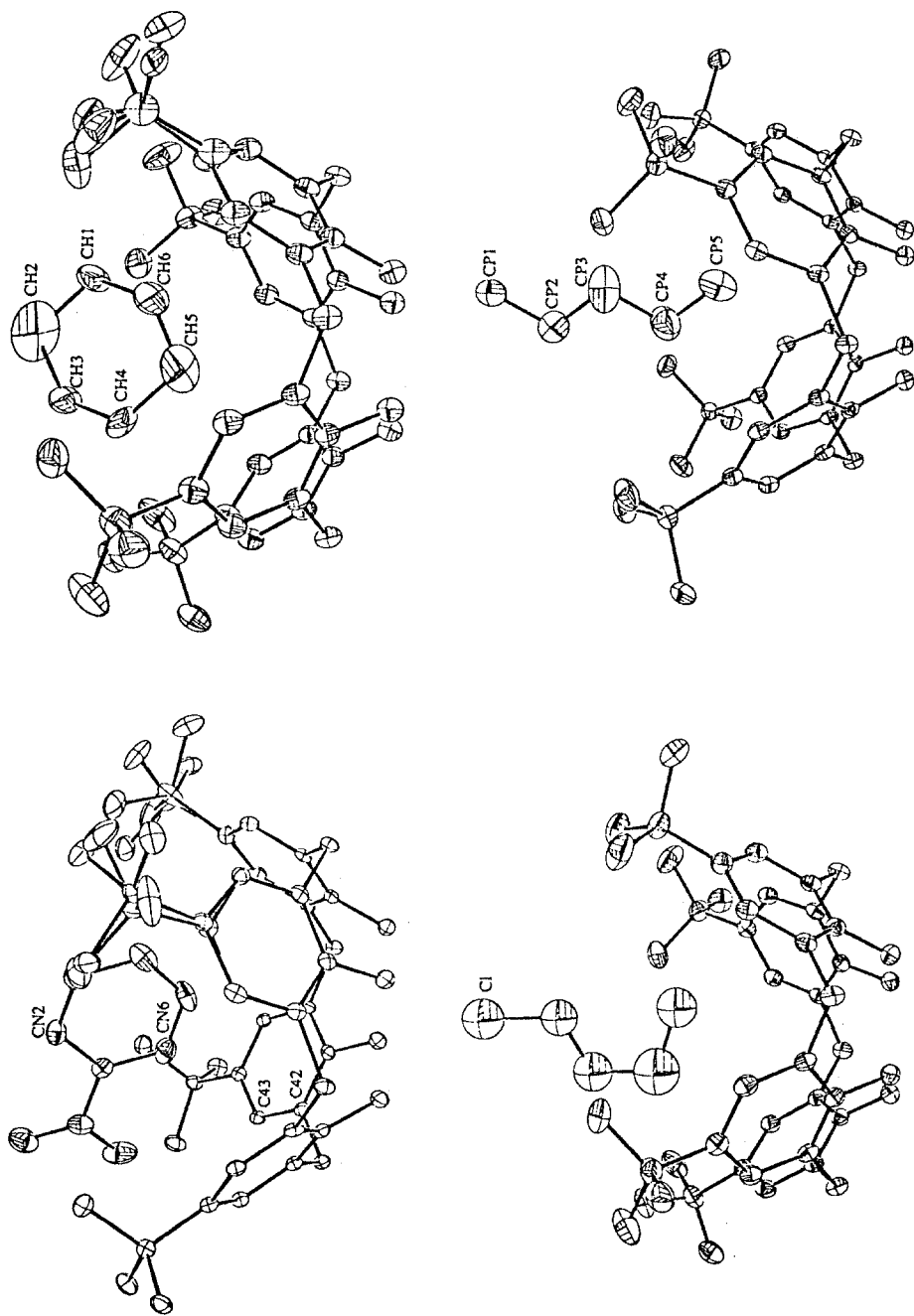
Figure 5. t-Butylcalix[4]arene-guest structures (clockwise from upper left): nitrobenzene, cyclohexane, *n*-pentane, and 1-chlorobutane.

Table II. Summary of diffraction data for C4A-guest compounds[a].

C4A-guest	Toluene	Toluene[b]	NB	n-Pentane	Cyclohexane	Chlorobutane
Formula	$C_{12.75}H_{16}O$	$C_{12.75}H_{16}O$	$C_{50}H_{61}NO_6$	$C_{12.25}H_{17}O$	$C_{12.5}H_{17}O$	$C_{12}H_{16.25}Cl_{0.25}$
Crystal system	tetragonal	tetragonal	orthorhombic	tetragonal	tetragonal	tetragonal
Space group	$P4/n$	$P4/n$	$Pc2_1n$	$P4/n$	$P4/n$	$P4/n$
a, Å	12.5540(3)	12.77259(23)	12.4355(4)	13.0230(19)	12.9446 (4)	13.0571(15)
b, Å	12.5540(3)	12.77259(23)	12.9346(5)	13.0230(19)	12.9446 (4)	13.0571(15)
c, Å	13.7665(17)	13.8068(5)	26.7560(12)	12.6190(12)	12.8156(25)	12.5986(15
V, Å^3	2169.7(6)	2252.43(9)	4303.7(3)	2140.2(4)	2147.4(4)	2144.4(4)
Z	8	8	2	8	8	8
ρ_{calc}, g cm^{-3}	1.124	1.089	1.191	1.119	1.134	1.148
Total # rflns	4963	4452	5465	2154	4655	4084
# unique rflns	2049	2157	5377	2045	2052	2046
# rflns $I \geq 2.5\sigma(I)$	1727	1385	5095	1641	1697	1549
R	0.051	0.046	0.041	0.048	0.051	0.091
R_w	0.077	0.063	0.057	0.070	0.079	0.138

[a]Conditions and collection details: 150 K; Enraf-Nonius diffractometer; graphite monochromator; CuKα 1.54056 Å; aperture 4.0 × 4.0 mm at a distance of 173 mm from the crystal; stationary background counts at each end of the scan (scan/background time ratio 5:1); peak and background counts determined with profile analysis procedure of Gabe *et al*: *J. Appl. Crystallogr.*, **22**, 384 (1989). $\sigma(F_0)$ based on counting statistics, function minimized $\Sigma w(|F_0| - |F_c|)^2$, where $w = [\sigma^2(F_0) + k(F_0)^2]^{-1}$, $R = \Sigma ||F_0| - |F_c|| / \Sigma |F_0|$, $R_w = (\Sigma w(|F_0| - |F_c|)^2 / \Sigma w |F_0|^2)^{1/2}$, and GOF $= [\Sigma w(|F_0| - |F_c|)^2 / (m - n)]^{1/2}$. Values given for R and R_w, are based on those reflections with $I \geq 2.5\sigma(I)$.
[b]290 K.

Structures of modified C4A compounds with nonaromatic compounds are known [8, 9, 11, 19–21,38], but involve polar or double-bonded guests; furthermore, these calix compounds are modified: by ring size, by incorporation of metals, or by modification of the upper or lower rim, resulting in an increase in the complexity of host–guest interactions. When CH-π interactions are discussed as stabilizing forces, specific C—H bonds that interact with the calix π system are not identified. There is an absence of structures of simple C4A compounds with aliphatic hydrocarbon guests, guests that would be expected to provide the best proof for the necessity of stabilizing CH-π interactions in host-guest compounds.

Table III summarizes the guest ^{13}C CP-MAS NMR spectral information of C4A–aliphatic compounds [39]. In all cases, the calix resonances show a 4-fold symmetric conical cavity. The difference in guest chemical shifts from solution and C4A inclusion ($\Delta\delta$) give an indication of the position of the guest fragment in the cavity: the more negative the $\Delta\delta$, the deeper the guest is included in the cavity. Entries 1–4 show insignificant $\Delta\delta$ values, suggesting the guests possess motions that are fast (on the NMR timescale) and average out the differences between the two ends of the aliphatic chain or ring. For propane, n-butane and n-pentane, this would be an end-over-end motion in addition to the dynamic disorder about the calix 4-fold axis. Since the $\Delta\delta_{Me}$ difference is not great, the methyl groups must jump between a site deep in the cavity (with a large $\Delta\delta_{Me}$) and one quite removed from the cavity (with a more solution-like value of δ_{Me}). Averaging between the two magnetically inequivalent sites leads to an intermediate value of $\Delta\delta_{Me}$.

We expected that end-over-end hydrocarbon motion would be retarded if a heavier atom was substituted for a terminal methyl group. As the increased size of the electron cloud of the halogen atom favours strong van der Waals interactions with the host, it might sit deep in the cavity and 'anchor' the aliphatic chain. The ^{13}C spectra of the 1-X-butanes (X = Br, Cl) differ from n-pentane in exhibiting a significant difference in methyl resonance shifts in the calix from those in solution. The shift in δ_{Me} thus suggests that the halogenated hydrocarbons may indeed be 'anchored' in the cavity, but instead of the halogen occupying the cavity, the terminal methyl is inserted deep in the calix cavity.

The dynamics of the 1:1 n-pentane–C_{60} inclusion compound have been studied with ^{13}C NMR [41]. n-Pentane undergoes three types of motion: (i) rotation about its main molecular axis, (ii) flipping of this axis between two sites related by a crystallographic mirror plane and (iii) end-over-end motion. The third motion is rapid (on the NMR timescale) at 303 K and thus gives rise to a single ^{13}C resonance line at δ 16.9 ppm. At 163 K, this motion freezes in and two methyl lines indicate distinct methyl groups (δ 15.0, 17.6 ppm). Figure 6 shows two ^{13}C CP-MAS NMR spectra of C4A-n-pentane. The low temperature spectrum shows single resonances for the terminal methyl and α-methylene groups which is very similar to the 290 K spectrum. Furthermore, the calixarene t-butyl lines remain sharp at 90 K which indicates the calix C_4 symmetry persists at this low temperature. Unlike the pentane-C_{60} inclusion compound, the two methyl groups of n-pentane in C4A are

Table III. Guest ^{13}C NMR chemical shifts (in ppm) of C4A-aliphatic compounds.

Entry	Guest	Carbon	Calix[a]	Solution[b]	$\Delta\delta$[c]
1	Propane	Me	14.5	15.4	−0.9
		C-2	15.9	15.9	0.0
2	*n*-Butane	Me	11.6	13.1	−1.5
		C-2	24.5	24.9	−0.4
3	*n*-Pentane	Me	12.3	13.7	−1.4
		C-2	23.5	22.6	+0.9
		C-3	d	34.6	d
4	Cyclohexane	C	26.4	27.6	−1.2
5	1-Bromobutane	Me	9.0	13.0	−4.0
		C-3	22.3	21.2	+1.1
		C-2	d	33.0	d
		C-1	36.0	34.7	+1.3
6	1-Chlorobutane	Me	8.7	13.0	−4.3
		C-3	20.5	20.0	+0.5
		C-2	35.6	34.7	+0.9
		C-1	45.0	44.3	+0.7
7	*n*-Hexane	Me	8.4	13.7	−5.8
		C-2	19.9	22.8	−2.9
		C-3	26.0	31.9	−5.9
8	*n*-Heptane	Me	8.7	13.8	−5.1
		C-2	22.8	22.8	0.0
		C-3	30.0	29.3	+0.7
		C-	32.3	32.2	+0.1
9	*n*-Dodecane	Me	12.1	14.8	−2.7
		C-2	23.0	23.3	−0.3
		C-3	33.8	32.8	1.0
		C-4	31.7	30.5	1.2
		C-5	31.2	30.5	0.7
		C-6	30.2	30.5	−0.3

[a]Referenced to hexamethylbenzene (δ 16.9 ppm). [b]From ref. 40, or spectra collected on Bruker 300 MSL spectrometer, CDCl$_3$ solvent. [c]$\Delta\delta = \delta$ (calixarene) − δ (solution). [d]Not observed.

dynamically averaged at 90 K. That the C4A architecture retains 4-fold symmetry even at 90 K and fails to collapse to a lower symmetry form indicates that the dynamic motion of averaging guest-host interactions is significant in carving out a symmetrical occupational space.

The cyclohexane, *n*-pentane, and 1-chlorobutane C4A structures are shown in Figure 5. Interestingly, the calix *t*-butylphenol groups show little (cyclohexane) or no (*n*-pentane, 1-chlorobutane) positional disorder, perhaps due to a more symmetrical shape of the dynamically-averaged guest which may minimize interactions
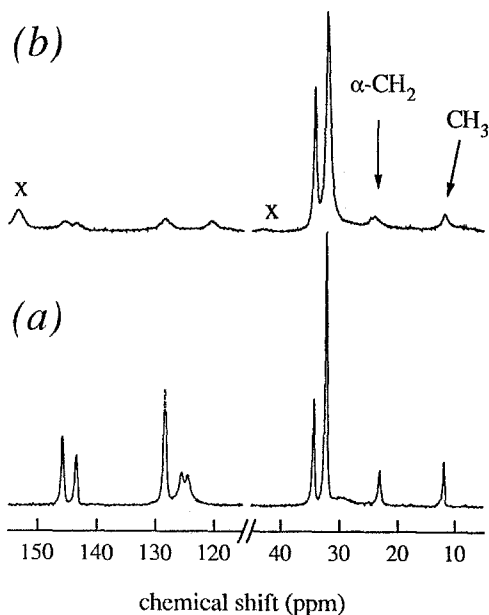
Figure 6. 50.3 MHz ^{13}C CP-MAS NMR spectra of C4A-*n*-pentane: (a) 290 K, (b) 90 K. X indicates spinning sidebands.

between the guest and host *t*-butyl groups. Substitution of a terminal methyl group of *n*-pentane by chlorine changes the aliphatic orientation in the corresponding C4A-guest structure and is consistent with the ^{13}C NMR data. The 'socket' position deep in the calix cavity is occupied not by the halogen, but by the terminal methyl. Furthermore, the halogen end of the chain is kinked, as opposed to the straight chain of the all-*trans* *n*-pentane.

The cyclohexane carbon (CH5) deepest inside the calix cavity is close to the host axis, and the line between CH5 and the carbon atom directly across the ring (CH2) is 13.1° off the calix C_4 axis. The CH5 atom is 4.15 Å above the plane defined by the four phenolic oxygens and is located 3.54 Å from the plane of the nearest phenyl ring, approximately equidistant (3.80 Å) from the lower three phenyl ring carbons. Deeper penetration by cyclohexane is prevented by steric interactions between CH6 and the adjacent phenyl carbons (CH6—C distances of 3.40, 3.49 and 3.52 Å). Other notable short contacts occur between the cyclohexane CH1, CH3 and the *t*-butyl carbons in the next layer (CH1, CH3—methyl distances are 3.58, 3.77 Å). Significantly, the cyclohexane CH5 C—H bonds are not oriented towards the phenyl ring but rather point to the space in between two adjacent phenyl rings.

Unlike the vast majority of C4A–guest structures, the *t*-butylphenol groups in C4A–*n*-pentane and C4A–chlorobutane show no disorder, perhaps due to minimal host-guest interactions. The long axis (CP1–CP5) of the *n*-pentane molecule is
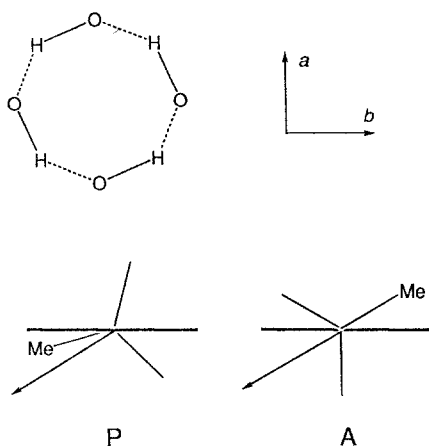
Figure 7. C4A chirality arising from the direction of the phenolic O—H bonds (top). The parallel (**P**) and anti-parallel (**A**) orientations of the *t*-butyl groups with respect to the direction of the phenolic O—H bond (bottom); the aromatic ring is indicated by the heavy black line and the O—H bond by the arrow. The **P** and **A** positions are related by rotation about the aromatic ring-C(Me)₃ bond.

tilted 2° from the calix 4-fold axis. The methyl group inside the cavity is 4.05 Å above the plane defined by four phenolic oxygens and 3.52 Å from the plane of the nearest phenyl ring, approximately equidistant (3.70 Å) from the bottom three phenyl carbon atoms of the phenyl ring. Short contacts occur between the protruding two pentane carbon atoms and the *t*-butyl methyls of the next layer (CP2—C distance of 3.37 Å and CP1—C distances of 3.67, 3.75 and 3.98 Å).

What, then, are the stabilizing interactions between guest and host? Clearly, for aliphatic guests, π_{guest}–methyl$_{calix}$ interactions are impossible, and reciprocal interactions between π_{calix}–methyl$_{guest}$ interactions [1, 20] are excluded by the absence of methyl groups in cyclohexane. In the three structures, there is no evidence for π-methyl interactions. If anything, the guest is positioned to *minimize* close contact with the calixarene aromatic group. A significant factor for the guest position seems to be the interaction of the guest in one calix–guest unit with similar units in the layer above it, which appears to 'push down' the guest into its calix cavity. For an 'absolute' understanding of guest–host interactions, additional information, such as the guest-free structure and the relative free energies need to be known.

A variety of C4A–guest structures affords further insight into the nature of the *t*-butylphenol disorder. In all cases that we have studied, the *t*-butylphenol positions appear to be linked to the direction of the phenolic hydrogen bonding at the base of the calix. The preferred position (P) has one C—CH₃ bond bent slightly inwards (5–10°) from the plane of the calixarene phenyl ring and pointing in the direction of the O—H bonds (Figure 7) while the alternate position (A) also has one C—CH₃ bond pointing inwards by 5–10° but opposed to the direction of the O—H bonds.
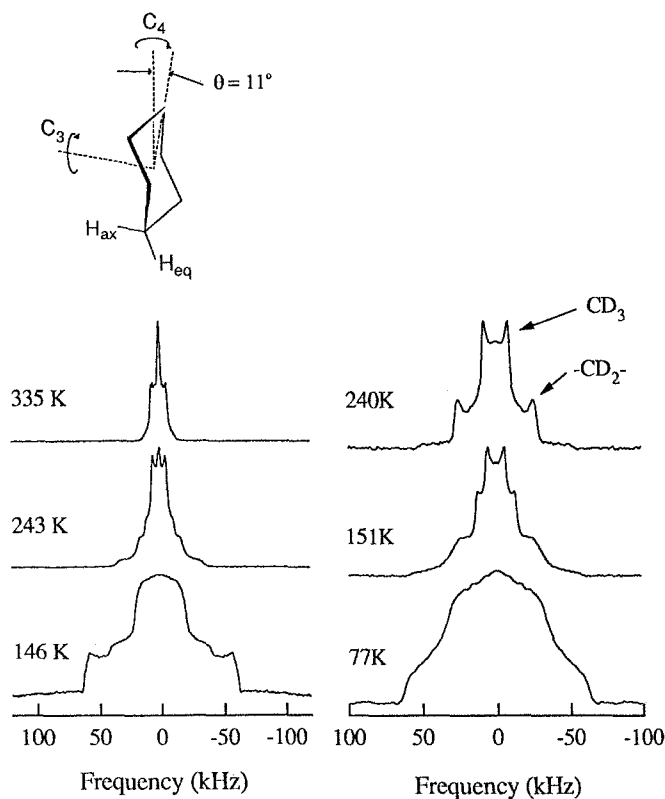
Figure 8. 30.1 MHz ^{2}H NMR spectra of C4A-cyclohexane-d_{12} (left) and C4A-pentane-d_{12} (right). The diagram illustrates the motions of cyclohexane.

This latter position is induced by a steric interaction between the guest and the host, and is accompanied by an outward bending of the host phenyl ring.

The variable temperature ^{2}H NMR spectra of C4A-cyclohexane-d_{12} (Figure 8) are consistent with the presence of three types of guest motion [33]: (a) cyclohexane rotation (in the chair conformation) about its C_3 molecular axis, which narrows the line due to the static guest by a factor of three, (b) the cyclohexane rotates about the calix C_4 axis and finally, (c) at higher temperatures, the cyclohexane inverts, i.e., the axial and equatorial hydrogens become equivalent (Figure 8). The 243 K lineshape is narrowed from the lineshape expected for $C_3 + C_4$ motions by an amount consistent with an angular tilt of the guest off the calix C_4 axis of $\theta = 11°$ (cf. XRD: 13°).

^{13}C NMR work suggests that there is still motional averaging of n-pentane at low temperatures. The variable temperature ^{2}H NMR spectra of C4A–n-pentane-d_{12} were collected in order to investigate further (Figure 8). The 77 K spectrum shows n-pentane to be undergoing axial molecular rotation ($\chi_{77}(CD_2) = 78.67$ kHz); the broadness of the line suggests a distribution of pentane motions in the

crystalline lattice, possibly due to defects in long-range periodicity. The central intensity arises from methyl group rotation which is in the intermediate motional regime. The 240 K fast motion limit spectrum shows two lines with intensity 1:1 arising from the methyl (χ_{240} = 23.60 kHz) and methylene deuterons (χ_{240} = 70.67 kHz), and is consistent with the following motions: rotation about the molecular axis, C_4 rotation about the calix axis, and for the methyl group, C_3 rotation. The end-over-end motion suggested by ^{13}C NMR is invisible to ^{2}H NMR. Narrowing of the methyl lineshape from the expected (χ = 26.22 kHz) is consistent with a tilt of the all-*trans* n-pentane off the calix C_4 axis by 15°, which is slightly larger than observed by XRD. It is also possible that the extra narrowing is due to the presence of gauche conformers [42]. The dynamic picture of the n-pentane is not yet fully understood, and ^{2}H NMR studies on 1-bromobutane-d_9 and n-pentane-3,3-d_2 C4A compounds are in progress towards that end.

5. Summary

A synoptic approach, the combination of XRD and NMR techniques, in assessing the structure and dynamics of t-butylcalix[4]arene host-guest inclusion compounds generates a more detailed insight into this class of compounds. Most significantly, further understanding of host disorder has been developed with beneficial consequence to the quality of the C4A-guest structural models. Positional and motional characteristics of the guest are accessible via NMR and can be beneficially incorporated with the XRD. Finally, it is anticipated that accurate structural models will facilitate broader understanding of the non-bonding host-guest interactions in inclusion compounds.

Acknowledgements

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