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A vibrational spectroscopic study of clathrates of resorcarene-based cavitands

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epoc ABSTRACT: By comparison of the fully assigned vibrational spectra obtained for resorcarene-based cavitands 2a and 2b, their clathrates with toluene and ethanol respectively, and free guest molecules, good structural models for the clathrates could be obtained merely based on Fourier transform infrared data. Using this novel technique, various different interactions between the host and guest in the solid state as well as the orientation of the included guest could be identified. In the case of cavitand 2a, the model obtained by this methodology could be validated by comparison with an experimental crystal structure analysis. Copyright © 2001 John Wiley & Sons, Ltd.
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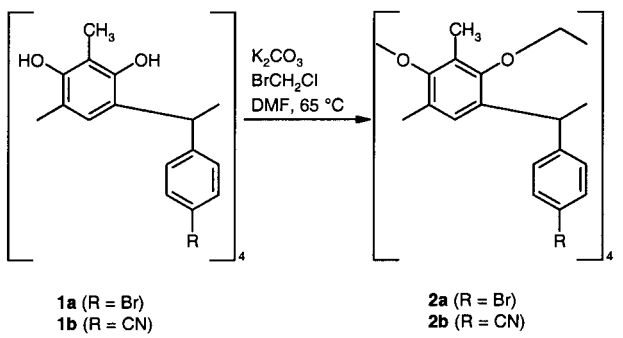
KEYWORDS: host–guest systems; resorcinarenes; calixarenes; supramolecular chemistry; vibrational spectroscopy

INTRODUCTION

Host–guest interactions of calixarenes and resorcarene-based cavitands with guest molecules are usually studied in the solid state by single-crystal structure determination.[1–3] However, there is still a considerable need for alternative methods that can be applied in cases when only limited amounts of non-crystalline material are obtainable. In the beginning of the calixarene-related chemistry, Fourier transform infrared (FTIR) spectroscopy was important to unravel the cyclic hydrogen bonding system at the lower rim fixing the *cone* conformation of these compounds.[1] Examples for the use of vibrational spectroscopy as an efficient tool to characterize host–guest complexes of calixarenes and resorcarene-based cavitands in the solid state and in solution are still scarce,[4–9] and still mainly limited to the investigation of hydrogen-bonded,[10–13] or surface-bound systems.[14,15]

Acid-induced cyclocondensation of 2-methylresorcinol with *para*-substituted benzaldehydes gives rise to the corresponding chair methylresorc[4]arenes **1a**, **b** in fair to excellent yields. Bridging of the eight phenolic groups is possible by the reaction of **1** with bromochloromethane using K_2CO_3 as base to give resorcarene-based cavitands **2a**, **b** having two adjacent aryl substitutents in the axial position and the two others in the equatorial position (Scheme 1 and Fig. 1).[16]

A single crystal structure determination of the cavitand **2a**[16] clearly shows a distinct interaction between the bromophenyl groups at the 'feet' of the cavitand skeleton with the cavity of a second macrocycle (Fig. 1). In contrast, for the *p*-cyanophenyl-substituted cavitand **2b** no single crystal structure determination was accessible. Therefore, we decided to use a thorough analysis of the vibrational spectra of resorcarene-based cavitands to gain



Scheme 1. Synthesis of resorcarene-based cavitands **2a** and **2b**

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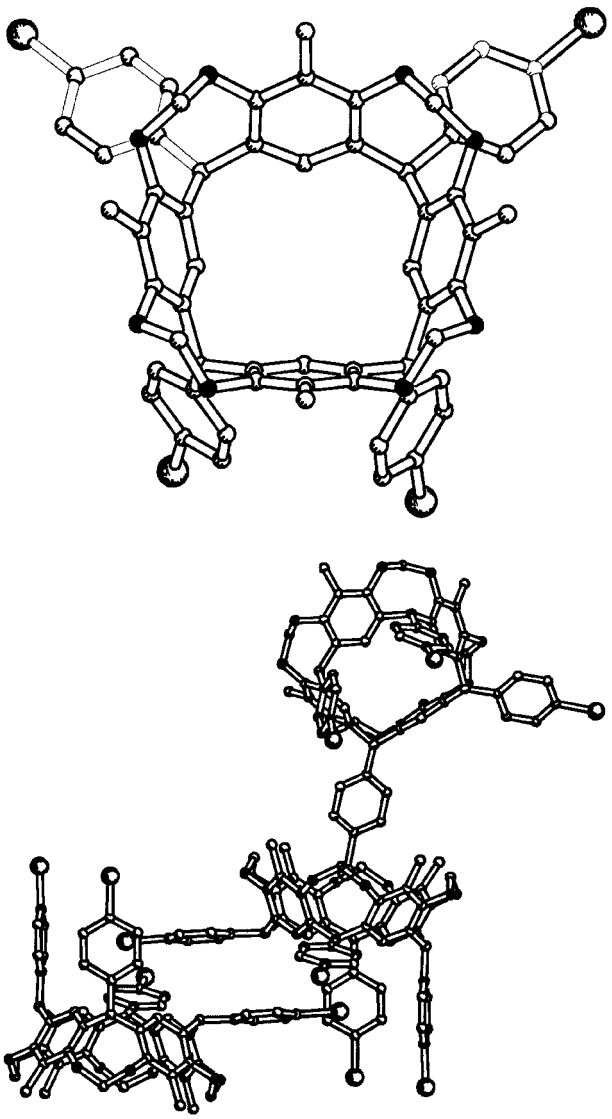

Figure 1. X-ray crystal structure of cavitand **2a** at 30% probability level. Hydrogen atoms and toluene solvent molecules are omitted for clarity. Reprinted with permission from Middel O *et al*, *J. Org. Chem.* 1998:63(23), 8259–8265. © 1998 American Chemical Society.

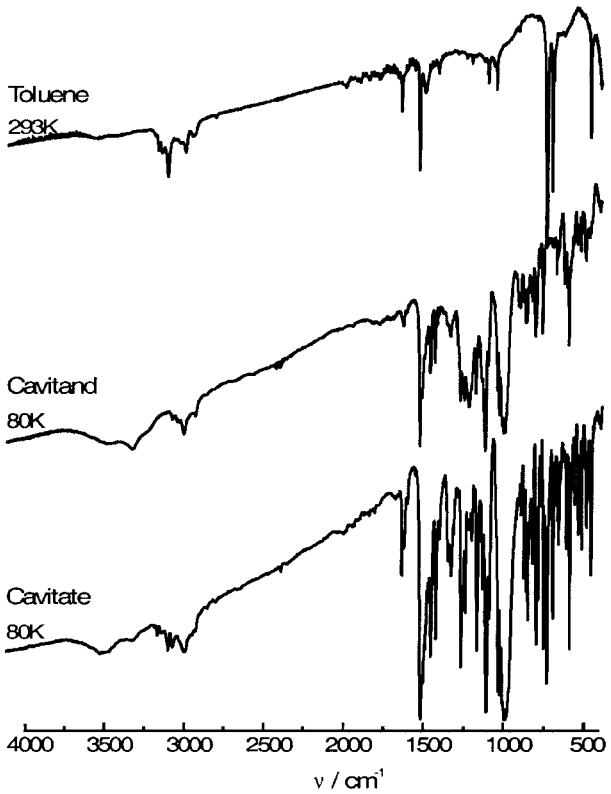

Figure 2. FTIR spectra of empty **2a, 2a**–toluene clathrate and pure toluene at 80 K

a deeper insight of the solid-state structure and inclusion properties of these compounds.

RESULTS AND DISCUSSION

General procedure for the vibrational analysis

Owing to the similar linear geometry of the substituents at the lower rim, cavitand **2b** (R = CN) was studied and compared with **2a** (R = Br) as a reference compound with known structure to validate the approach.

Materials for the FTIR spectroscopic studies could be obtained by recrystallization of the crude cavitand from suitable solvents yielding solvent clathrates of the host compounds. Cavitand **2a** gives a clathrate with toluene, and **2b** with ethanol. The number of solvent molecules included in the crystal lattice could be easily deduced from a thermogravimetric analysis.[17]

From a comparison of the fully assigned FTIR spectra using the Wilson assignment mode[18] of the solvent clathrates **2a**–toluene (1:4) or **2b**–EtOH (2:1) with spectra obtained for the solvent-free cavitands and pure solvents (Figs 2 and 3), it is possible to gather information about the interactions between the solvent molecules and the macrocycle. Differences of the absorption of free and enclathrated species give rise to complex-induced shifts (CISs). These data are of similar importance as CIS values stemming from NMR experiments in solution. Furthermore, band splitting and changes of intensities of analogous absorptions give additional information about the symmetry of the corresponding intermolecular interactions. To facilitate the comparison of intensities, clusters of absorption bands are compared individually with the most intense absorption of the cluster scaled to 100% independently from the rest of the spectrum.

However, this approach is not suitable for studying interactions between individual host molecules, because no reference system, *i.e*. a host molecule that does not show any interaction with a neighbour, is accessible. In

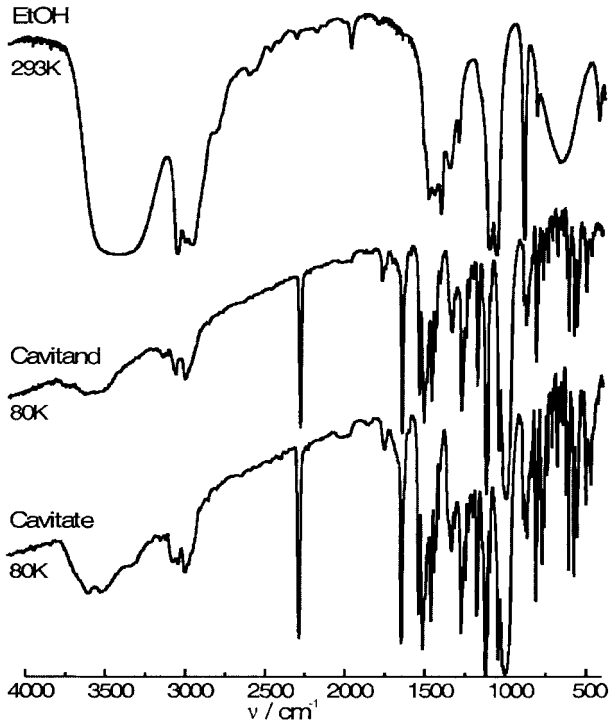

Figure 3. FTIR spectra of empty **2b, 2b**–ethanol clathrate and pure ethanol at 80 K

this case, a reference system can be used based on model compounds that reflect important parts of the molecule under investigation, namely a *p*-cyanophenyl (part A in Fig. 4), a methylene bridge (part B), a C—O—C—O—C (C), O—CH_2 (D), a methyl group (E) and a pentasubstituted benzene ring (F).

The chosen model substances **3**–**6** reflect the bond strengths between atoms when dealing with stretching modes and a similar substitution pattern at the phenyl rings in the case of deformation vibrations. In the latter case, the weight of the substituents must reflect the real situation more than the actual bond strength. The choice of model substances, especially when using data of pentasubstituted phenyl rings, is somewhat limited.[19]

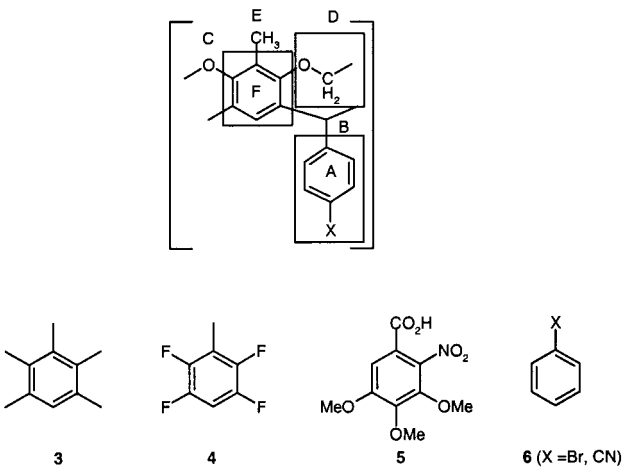

Figure 4. Numbering scheme for the vibrational analysis of the cavitand **2b** and model substances used for the analysis

Vibrational analysis of cavitand 2a

The relevant FTIR spectra for the analysis of cavitand **2a** and its toluene clathrate are shown in Fig. 2. According to the X-ray analysis and NMR data in solution,[16] the cavitand possesses a low symmetry, the highest point group being C_s with one mirror plane between the axial and equatorial *p*-bromophenyl groups cutting opposite tolyl units; in the case of deviation from this symmetry, C_1 is the corresponding point group. Neglecting interaction terms in the potential function between the methyl group and the aromatic ring, the equation for toluene can be factorized as if the molecule possessed C_{2v} symmetry when the vibrations are divided into planar and nonplanar symmetry species. All vibration modes are Raman active, whereas only the A_1, B_1 and B_2 modes are IR active. The point group is C_s; the site group is C_1. Hence, it follows for included toluene that all vibration modes are Raman- and IR-active and for C_1 the species is A.

The thermogravimetric data give, in accordance with the crystal structure, a host–guest ratio of 1:4, resulting in a highly solvated structure. Theoretically, one should expect a band splitting into four components in accordance with the different orientations of the four toluene molecules in the crystal lattice. This can only be observed for the strongest IR bands of toluene (bands ν_4, ν_{11} and ν_{16a}; see Supporting information). Furthermore, the relative intensities of the components should be similar. Actually the ratio is 1:1:0.25:0.25. This can be easily explained by the loss of solvent molecules at room temperature (e.g. during the preparation of the KBr pellets). Almost all other bands split into two components with similar intensity (the other two components are unverifiable, because the overall intensity of the band is too weak).

Compared with pure solvent, entrapped toluene shows more absorption bands, especially overtones and combination tones. This is in accordance with a solvated structure. On the other hand, there are some bands that are typical for isolated molecules, like in the gaseous state, e.g. ν_4, ν_{11}, ν_{18a}, and ν_{18b}. This observation is in accordance with the interpretation that there are interactions between molecules with the same orientation along channels in the crystal lattice but no interactions between molecules with different orientations.

Most absorptions are shifted towards lower frequencies: the shift is up to 39 cm^{-1}, and the average shift is about 12 cm^{-1}; some absorptions are moderately shifted towards higher frequencies, the average shift being about 6 cm^{-1}. This can be explained as a complexation-induced

shift. When an absorption band of a 'free' molecule is split into two components it is conspicuous that the splitting pattern is not symmetrical.

Comparing the solvent-free cavitand with its toluene clathrate, no significant shift of the absorption frequencies can be observed. This is in accordance with the rigid structure of the cavitand. Band splitting of some frequencies of parts A, E, and F (Fig. 4) into two components may be an effect of the equatorial and axial orientation of the *p*-bromophenyl units and the anisotropy of the potential field. The number of components can be correlated with the mirror plane and the C_s symmetry. The complexation-induced shifts obtained by comparing the clathrate with the incremental system based on model substances provide evidence for the following host–host and host–guest interactions: CH/π interaction between the *p*-bromophenyl substituent and the —O—CH_2—O— bridge (A→C/D); interaction between two *p*-bromophenyl units (A→A); and CH/π interactions between the toluene in the crystal lattice and parts A and F (Fig. 4).

Vibrational analysis of cavitand 2b

According to the NMR data[16] cavitand **2b** possesses a low symmetry, the highest point group being C_s with one mirror plane between the axial and equatorial *p*-cyanophenyl groups; in the case of deviation from this symmetry, C_1 is the corresponding point group. Assuming free rotation of the alkyl chain rotating around the OH group, gaseous ethanol belongs to a group isomorphic to C_{3v}. In the liquid and solid state the rotation is hindered; the corresponding point group is C_s, and the site group is C_1. Hence, it follows for included ethanol that all vibrations are IR- and Raman-active and the species are C_s (A′, A″) or C_1 (A). In the liquid state (Fig. 3) hydrogen bonds exist between the ethanol molecules, which results in broadening of the OH vibrations.

From thermogravimetric data, a host–guest ratio of 2:1 can be deduced. Thus, only one ethanol molecule is located near or inside the cavitand **2b**. According to this, no further band splitting due to different orientations of the solvent molecules can be observed. This is in contrast to the X-ray analysis of the *p*-bromophenyl-cavitand **2a**, wherein four toluene molecules are related to each cavitand. The OH group of the ethanol is fixed inside the cavity, probably parallel to the mirror plane, freezing the OH/π interaction. This results from the observation of a doublet for ν(OH) and δ(OH). Such doublets are characteristic for monomeric alcohols, the doubling being about 200 cm^{-1} and 60 cm^{-1} respectively. The δ(OH) band (1385 cm^{-1}) and the γ(OH) band (644 cm^{-1}) are very sharp, indicating a lack of any hydrogen bonding; the OH group of entrapped ethanol is fixed. According to the structure of the cavitand **2b** and the absence of any hydrogen bonding, the OH group must be located in the hydrophobic cavity, otherwise one would expect hydrogen bonding towards the O atoms in the methylene bridges or between different ethanol molecules. The doublet is attributed to an asymmetric potential field about the CO bond, to which the H is attached. This anisotropy may be caused by steric effects and rotational isomerism, e.g. by the axial and equatorial *p*-cyanophenyl units, which spread out in an asymmetric potential field. Perhaps one *p*-cyanophenyl group inside the cavity induces a further special steric effect.

The alkyl chains of entrapped ethanol guest molecules rotate freely around the locked OH group. All frequencies are shifted towards lower frequencies, the shift ranging from 9–17 cm^{-1}. Some low-lying vibrations, which cannot be assigned to any of the modes of the subunits, have to be characterized as specific for the cavitand *in toto*. They are denoted as 'cavity ring mode'. Comparison of the free cavitand and the host–guest complex shows that there is no significant shift of the frequencies. This is in accordance with the rigid structure of the cavitand and similar to that found for cavitand **2a**. Band splitting of some frequencies of parts A, E, and F (Fig. 4) into two components may be an effect of the equatorial and axial orientation of the *p*-cyanophenyl units and the anisotropy of the potential field. The number of components can be correlated with the mirror plane and the C_s symmetry.

The complexation-induced shifts obtained by the comparison of the clathrate of ethanol with **2b** provide evidence for the following host–host and host–guest interactions: CH/π interaction between *p*-cyanophenyl and the —O—CH_2—O— bridge (A→C/D); π/π interaction between two *p*-cyanophenyl units (A→A); OH/π interaction (EtOH→A); and CH/π interaction from the freely rotating alkyl chain of EtOH to the *p*-cyanophenyl group (EtOH→F).

CONCLUSION

For studying possible host–guest interactions and conformational properties, a new empirical strategy for the vibrational analysis of resorcarene-based cavitands was developed. The cavitand structure was subdivided into chemically reasonable subunits. Assuming that the vibrational modes of the latter are more or less characteristic, comparisons were made of the vibrations of the whole cavitand with those of model substances equivalent to the subunits. Using this approach, important types of host–guest interaction can be identified and classified; the orientation of the included guest can be determined. Therefore, in cases when no single crystal structure determination of the host–guest clathrate is accessible, good structural models for the solid state can be obtained and interactions between host–guest, guest–guest and host–host can be identified merely based on FTIR data. For cavitand **2a**, the model obtained by this methodology could be validated by comparison with an experimental crystal structure analysis.

EXPERIMENTAL

The synthesis of cavitands **2a** and **2b** and the single crystal structure determination of **2a** have been described previously.[16] IR spectra were recorded on an IFS 113v FTIR spectrophotometer (Bruker) using KBr windows and a DGTS detector, the resolution being about $0.5\,cm^{-1}$. Raman spectra were recorded a Dilor XY Raman-laser spectrophotometer (multi- and single-channel detector, resolution $1\,cm^{-1}$) using an Ar-laser (coherent, excitation line 514.53 nm). The temperatures of the samples were 293 K and 80 K respectively. The host–guest ratios of the samples used for the IR analysis were determined by thermogravimetric analysis, as described previously.[17]

Supporting material

Six tables containing fully assigned IR data of cavitands **2a**, **b**, their clathrates with toluene and ethanol, respectively, as well as the corresponding model substances **3–6** are available as supporting information at http://www.wiley.com/epoc.

Acknowledgements

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REFERENCES

1. Gutsche DC. *Calixarenes*. Royal Society of Chemistry: Cambridge, 1989.
2. Gutsche DC. *Calixarenes Revisited*. Royal Society of Chemistry: Cambridge, 1998.
3. Vicens J, Böhmer V (eds). *Calixarenes: a Versatile Class of Macrocyclic Compounds. Topics in Inclusion Science*. Kluwer Academic Publishers: Dordrecht, 1991.
4. Schatz J, Schildbach F, Lentz A, Rastätter S, Schilling J, Dormann J, Ruoff A, Debaerdemaeker T. *Z. Naturforsch., Teil B* 2000; **55**: 213.
5. Lutz BTG, Astarloa G, van der Maas JH, Janssen RG, Verboom W, Reinhoudt DN. *Vib. Spectrosc.* 1995; **10**: 29.
6. Nissink JWM, Boerrigter H, Verboom W, Reinhoudt DN, van der Maas JH. *J. Chem. Soc., Perkin Trans. 2* 1998; 1671.
7. Nissink JWM, Boerrigter H, Verboom W, Reinhoudt DN, van der Maas JH. *J. Chem. Soc., Perkin Trans. 2* 1998; 2541.
8. Nissink JWM, Boerrigter H, Verboom W, Reinhoudt DN, van der Maas JH. *J. Chem. Soc., Perkin Trans. 2* 1998; 2623.
9. Paci B, Amoretti G, Arduini G, Ruani G, Shinkai S, Suzuki T. *Phys. Rev. B Condens. Matter* 1997; **55**: 5566.
10. Kanters JA, Schouten A, Steinwender E, van der Maas JH, Groenen LC, Reinhoudt DN. *J. Mol. Struct.* 1992; **269**: 49.
11. Brzezinski B, Urjasz H, Zundel G. *J. Phys. Chem.* 1996; **100**: 9021.
12. Frkanec L, Visnjevac A, Kojic-Prodic B, Zinic M. *Chem. Eur. J.* 2000; **6**: 442.
13. Rudkevich DM. *Chem. Eur. J.* 2000; **6**: 2679.
14. Moreira WC, Dutton PJ, Aroca R. *Langmuir* 1994; **10**: 4148.
15. Nissink JWM, van der Maas JH. *Appl. Spectrosc.* 1999; **53**: 528.
16. Middel O, Verboom W, Hulst R, Kooijman H, Spek AL, Reinhoudt DN. *J. Org. Chem.* 1998; **63**: 8259.
17. Schatz J, Schildbach F, Lentz A, Rastätter S. *J. Chem. Soc., Perkin Trans. 2* 1998; 75.
18. Herzberg G. *Molecular Spectra and Molecular Structure. II. Infrared and Raman Spectra of Polyatomic Molecules*. Van Nostrand Reinhold Company: New York, 1945.
19. Varsányi G. *Assignments for Vibrational Spectra of Seven Hundred Benzene Derivatives*, vol. 1. London, 1974.