Thermodynamic study of the complexes of calix[4]naphthalenes with [60]fullerene in different solvents

Shehadeh Mizyed,[a] Paris E. Georghiou *[a] and Muhammad Ashram [b]

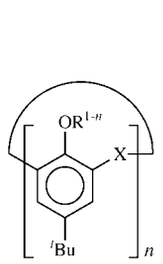
[a] *Department of Chemistry, Memorial University of Newfoundland, St. John's, Newfoundland, A1B 3X7 Canada*
[b] *Department of Chemistry, Mu'Tah University, Al-Karak, Jordan*

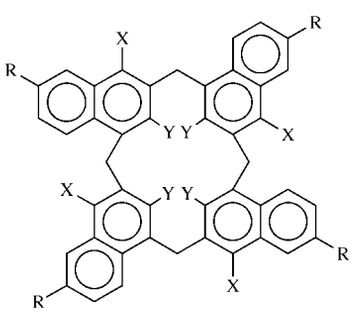
Received (in Cambridge, UK) 24th September 1999, Accepted 22nd November 1999

Calix[4]naphthalenes are a class of molecules which possess deeper cavities than those of the analogous calix[4]arenes. Preliminary data obtained for the complexation of [60]fullerene ("C_{60}") with the C_4-symmetrical *endo*-calix[4]-naphthalene **3** and its *tert*-butyl-substituted derivative **4** show that they form supramolecular 1 : 1 complexes with C_{60} in benzene, toluene or CS_2 solution with relatively high association equilibrium constants (K_{assoc}). Reported herein are thermodynamic parameters and additional K_{assoc} determined for the complexation of C_{60} and calix[4]naphthalenes **3** and **4** which show that both a solvophobic effect and π–π interactions are major driving forces for the complexation process.

Introduction

In 1994, Atwood *et al.*[1] and Shinkai *et al.*[2] reported that *p-tert*-butylcalix[8]arene (**1**) can be used to selectively sequester [60]-fullerene ("C_{60}") from a mixture containing C_{60} and [70]fullerene ("C_{70}"). This is accomplished by the formation of a 1 : 1 clathrate in which a C_{60} guest molecule is bound within the cavity of the host molecule **1**. Several studies have since been published which have shown that C_{60} also forms supramolecular complexes with various other derivatives of calix[*n*]arenes, calixresorcinarenes and cyclotriveratrylene.[3] Some of these reports describe formation of solid clathrates with accompanying X-ray structures, while others describe solution studies from which association equilibrium constant values were determined. Most of the data reviewed by Danil de Namor[4] concern thermodynamic studies of charged ionic guests with calix[*n*]-arene hosts, conducted in polar organic solvents (*e.g.* methanol, acetonitrile, benzonitrile), or in aqueous solution. With the exception of the data reported by Shinkai *et al.*[5] to the best of our knowledge there are no other thermodynamic data that have been reported for complexation of calix[*n*]arenes with C_{60} in nonpolar organic solvents.





1: R^1-R^n = H; X = CH_2; n = 8
5: R^1-R^n = H; X = CH_2; n = 5
6: R^1-R^n = H; X = CH_2O; n = 3
7: R^1-R^n = H; X = CH_2; n = 4
8: R^1-R^3 = H; R^4 = $SOCF_3$; X = CH_2; n = 4

2: R = Y = H; X = OH
3: Y = OH; R = X = H
4: Y = OH; R = ^{t}Bu; X = H

Calix[4]naphthalenes are a class of molecules which possess deeper cavities than those of the analogous calix[4]arenes. In 1993[6] and 1995[7] we reported the synthesis of all four *exo*-calix[4]naphthalene isomers which are methylene-bridged cyclic oligomers of 1-naphthol. The C_4-symmetrical isomer is depicted as structure **2**. In 1999 we reported that the corresponding C_4-symmetrical *endo*-calix[4]naphthalenes **3** and its *tert*-butyl-substituted derivative **4**, form supramolecular 1 : 1 complexes with C_{60} in benzene, toluene or CS_2 solution, and also reported the respective association equilibrium constants (K_{assoc}) of the complexes in each of these solvents.[8] It was noted in this report that the K_{assoc} values increased from benzene to toluene to CS_2 and the hypothesis was presented that this trend could be due to a solvophobic effect.[9] We herein report that these thermodynamic parameters, ΔH and ΔS, for the complexation of calix[4]naphthalenes **3** and **4** with C_{60} in each of the three solvents, is consistent with the hypothesis.

Other factors which determine the nature of the supramolecular complex formation between hosts such as *e.g.* calixarenes or cyclodextrins (and presumably, calixnaphthalenes) and non-polar or polar guests can also be delineated by analysis of the relationship between association equilibrium constants and the corresponding enthalpy and entropy changes.[10] It has been shown, for example, that the slopes and intercepts from the observed linear $T\Delta S$ *vs* ΔH plots can be used as quantitative measurements respectively, of the extent of conformational changes of the host, and of host–guest desolvation involved in complex formation.[10–12] The thermodynamic data reported herein are interpreted in these contexts and with reference to published data on other similar complexation phenomena.

Results and discussion

Supramolecular 1 : 1 complex formation between calix[4]naphthalene **4**, for example, with C_{60} in solution, can be represented by eqn. (1):

$$C_{60} + \mathbf{4} \rightleftharpoons C_{60}\cdot\mathbf{4} \quad (1)$$

The corresponding association equilibrium constant ("stability constant") K_{assoc} for **4** can be defined by eqn. (2), and is

$$K_{assoc} = [C_{60}\cdot\mathbf{4}]/[C_{60}][\mathbf{4}] \quad (2)$$

calculated on the basis of the corresponding Benesi–Hildebrand relationship,[13] eqn. (3), where ΔA is the absorbance

$$[C_{60}]/\Delta A = 1/\Delta\varepsilon + 1/(\Delta\varepsilon K_{assoc}[\mathbf{4}]) \quad (3)$$

This journal is © The Royal Society of Chemistry 2000

Table 1 Thermodynamic and K_{assoc} values for C_{60} complexes with **3** and **4** in toluene, benzene and carbon disulfide, at 298 K

Compound	Solvent	ΔH/kJ mol^{-1}	ΔS/J mol^{-1} K^{-1}	$T\Delta S$/kJ mol^{-1}	K_{assoc}
3	Toluene	−77.4 ± 1.8	−206.8 ± 4.7	−61.6 ± 8.5	661 ± 51
	Benzene	−65.4 ± 1.4	−167.1 ± 3.6	−49.8 ± 5.0	475 ± 40
	CS_2	−38.1 ± 0.8	−61.7 ± 1.3	−18.4 ± 1.0	2692 ± 78
4	Toluene	−59.7 ± 1.3	−144.4 ± 3.1	−43.0 ± 4.0	708 ± 91
	Benzene	−48.2 ± 1.1	−115.4 ± 2.5	−34.4 ± 2.8	302 ± 20
	CS_2	−30.9 ± 0.8	−34.4 ± 1.4	−10.3 ± 1.1	4018 ± 156

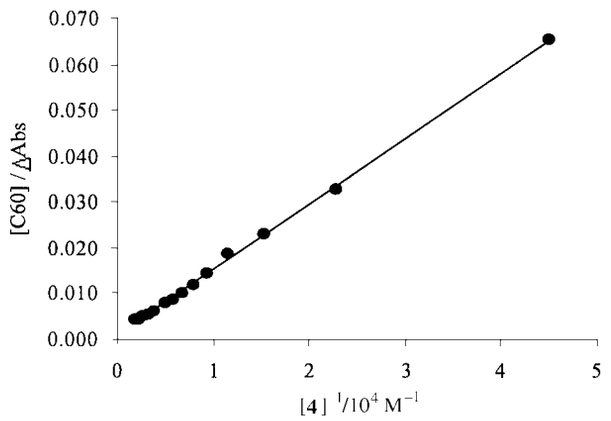


Fig. 1 Double-reciprocal plot of data for the C_{60}·**4** system in toluene solution at 25 °C.

change at $\lambda = 430$ nm of a solution of C_{60} in the appropriate solvent, upon the successive addition of **4**; $\Delta\varepsilon$ represents the difference in the molar extinction coefficient between the C_{60}·**4** complex and that of uncomplexed C_{60}.

A typical double reciprocal (Benesi–Hildebrand) plot for the C_{60}·**4** complexation process in toluene solution, for example, determined by eqn. (3) is linear ($r^2 = 0.998$) as shown in Fig. 1, with an intercept of 1.01×10^{-3} and slope of 1.43×10^{-6}. K_{assoc} values in each case are calculated by dividing the intercept by the slope (determined by linear regression analysis) of the respective double reciprocal plot. Table 1 lists the mean K_{assoc} values determined at 25 °C for C_{60} and **3** or **4** in each solvent.

Plots of $1/T$ *vs.* $\log_{10} K_{assoc}$ at five different temperatures for C_{60} and **3** or **4** in each of the three solvents tested are also linear and have positive slopes, indicating that the complexation process is exothermic and thus driven by favourable enthalpy changes. A typical plot for C_{60} and **4** in toluene for example, also gives a straight line ($r^2 = 0.977$) with a slope of 3.11×10^3 and an intercept of −7.54. All of the ΔH values determined for C_{60} and **3**, or **4**, in each solvent were exothermic and are listed in Table 1. The ΔH values for the complexation of C_{60} and **3** or **4** in toluene solution are higher than those noted for the same solvent, by Shinkai and Ikeda in their study of the complexation of C_{60} and *tert*-butylcalix[5]arene **5**, or *tert*-butylhexahomotrioxacalix[3]arene **6**.[5] Presumably, the extra fused aromatic rings on each naphthalene group in our examples allow for additional attractive π–π interactions. These additional interactions can be either due to the presence of the two extra π-bonds per naphthalene unit as compared with the phenyl groups in **5** and **6**, or simply due to the fact that the naphthalene rings result in the formation of a deeper and wider cavity, thus potentially allowing for better contact between host and guest.[14] It is notable that the ΔH values for **4** are lower than those for **3**. This could imply that the *tert*-butyl-methyl · · · π interactions between the methyl groups of the *tert*-butylcalixarene and the π-system of a guest molecule which were noted by Andreetti *et al.*[15a–d] to be important considerations, are not factors here. Such interactions accounted for the clathrate formation between toluene and *tert*-butylcalix[4]arene **7** observed by Andreetti *et al.*, and also for an unusual clathrate formed between benzophenone and *tert*-butylcalix[4]arene monotriflate (**8**) observed by ourselves.[16]

It is possible, however, to rationalize this apparent contradiction by considering that in the present case, the major attractive interactions for complex formation between C_{60} and **3** are the π–π interactions between C_{60} and both of the fused aromatic rings in each naphthalene unit *via* a deep-cavity inclusion. In the case of complexation between C_{60} and **4** however, a shallower penetration of the guest molecule may be occurring, wherein the *tert*-butyl-methyl · · · π interactions may be the dominant ones, thus sterically inhibiting potentially more effective π–π interactions between the C_{60} guest and the naphthalene rings. Despite the above considerations however, the K_{assoc} values for the C_{60}·**4** complex are higher than the corresponding values for the C_{60}·**3** complex.

The values of both ΔH and ΔS obtained become more negative as the K_{assoc} values increase, and the ΔH values are opposite to those that would be predicted simply using the solubility values for C_{60} in benzene (1.4–1.9 mg cm^{-3}) and toluene (2.1–3.2 mg cm^{-3}).[17] However, Haino *et al.*[18] have argued that complex formation competes against the solvation of C_{60} in these apolar solvents. The implication therefore would be that in the present study, the ΔH values measured for **3** or **4** in benzene should be higher than the corresponding values in toluene, which is not the case. Nevertheless, if the lower solubility values reported by Letcher *et al.*[19] for C_{60} in benzene (0.89 mg cm^{-3}) and toluene (0.54 mg cm^{-3}) are considered instead, our observed ΔH values are consistent with the trends in the solubilities of C_{60} in toluene, benzene and CS_2, respectively. Other studies[20–22] involving complexation between various calix[*n*]arene derivatives and C_{60} in toluene and benzene solution have reported similar K_{assoc} trends to ours.

Table 1 also shows that all of the ΔS values are negative, indicating that while complex formation is enthalpy favoured, it is also entropy disfavoured. Formation of the complexes therefore results in a more ordered system, possibly due to the freezing of the motional freedom of both the guest and the host molecules. Tao and Barra have offered a similar rationale for the data that they observed with their particular system.[10] The magnitudes of the entropy changes observed in CS_2, benzene and toluene, can be rationalized as follows. During formation of the complex, solvent molecules within the cavity of each calix[4]naphthalene host are displaced by a C_{60} molecule. It is proposed that upon complex formation with C_{60} more CS_2 solvent molecules are displaced than are benzene or toluene molecules. Thus, there is a larger entropy gain achieved from the displacement of CS_2 molecules compared to the other two solvent molecules. On the other hand, a more ordered state (entropy loss) can result in the case of toluene and benzene due to the solvation of the complex by a "face-to-face" interaction[23] of these solvent molecules around the complex. This is due to the π–π interactions which are possible between solvent benzene, or toluene with the naphthalene rings of the calix[4]naphthalene molecules, and also with the "aromatic" rings of the C_{60} guest within the complex. The higher ΔH values observed in toluene and benzene solution as compared to CS_2 can also be rationalized in this way. It has been suggested[24] that a factor which could possibly contribute to the unusual binding trends observed for the different solvents may be desolvation of

the fullerene occuring to a lesser degree with the smaller CS_2 molecule as compared with the aromatic solvents.

The entropy changes observed for the complexation of C_{60} and **3** in toluene and benzene solution are larger than those observed for **4**. This reflects the fact that **3** is known to be conformationally more flexible than **4** in solution,[25] even though both may become locked in a cone conformation as a result of their complexation with C_{60}, and despite the fact that the rotational freedom inherent in the *tert*-butyl groups on **4** would be expected to add to the entropy of the latter host molecules. It has also been suggested by a referee[24] that a higher degree of residual solvation could also provide some explanation for the smaller entropy loss and hence the stronger binding with the less tight complexes with the *tert*-butyl host, **4**.

A linear relationship exists between $T\Delta S$ and ΔH (slope = 0.90, intercept = 5.0; $r^2 = 0.99$). Such linear relationships are commonly referred to as a compensation effect, although Petersen[26] pointed out that these relationships can be deceptive. Nevertheless, several authors[10–12] have proposed recently that the slopes from $T\Delta S$ *vs.* ΔH plots derived from host–guest complexation studies can be rationalized in terms of the degree of conformational changes of the host during the complexation and that the intercepts can be rationalized in terms of the extent of desolvation upon complexation. Using these arguments, the magnitude of the slope implies that the C_{60}·**3** and C_{60}·**4** complexes are accompanied by large conformational changes and extensive desolvation, as seen from the relatively high intercept value obtained.

In conclusion, thermodynamic parameters and association equilibrium constants have been determined for the complexation of C_{60} and calix[4]naphthalenes **3** and **4** which have shown that a solvophobic effect and π–π interactions are major driving forces for the complexation process.

Experimental

Toluene (BDH, Scintillation Grade) was distilled over sodium metal with benzophenone prior to use. Benzene (ACP Chemicals Inc., A.C.S grade, 99%) and CS_2 (Aldrich Chemical Company, Inc., Spectrophotometric Grade, 99+%) were used without further purification. C_{60} (99.5%) was purchased from Aldrich. Calix[4]naphthalenes **3** and **4** were prepared according to methods previously described.[6–8] UV–VIS absorption spectra recorded on a HP 8452A diode array spectrophotometer with thermostated cell compartments. Temperatures were recorded to ±0.1 °C with a thermocouple (Kiethley Model 163 digital voltmeter).

To obtain the association equilibrium constants K_{assoc} corresponding to complex formation, changes in absorbance (ΔA) as a function of calix[4]naphthalene concentration were determined. A 2.50 ml aliquot of C_{60} solution (*ca.* 1.00×10^{-4} M in benzene, toluene or CS_2) was placed in a quartz cell, to which 0.050 or 0.10 ml aliquots from a stock solution (*ca.* 1.00×10^{-3} M) of **3** or **4** (*vide infra*) were added. After each addition and after homogenization of the resulting solutions, the absorption spectra were recorded at $\lambda = 430$ nm. At least ten data points were measured in each run. Blank solutions consisting of only the solvent were measured before each experiment. A solution of C_{60} in the appropriate solvent was used as the "solvent" with which to prepare the solutions containing **3** or **4**, in order to maintain the concentration of C_{60} constant during the experiment (mole fraction method). Duplicate data sets were obtained for each run. Absorbance was plotted *versus* concentrations of **3** or **4**.

Linear double reciprocal (Benesi–Hildebrand plots) plots (*e.g.* Fig. 1) were used to determine K_{assoc} values from the slope and intercept, obtained from linear regression analyses. Values for K_{assoc} were determined at five different temperatures (288–308 K). From the linear plots (*e.g.* Fig. 2) of log K_{assoc} *versus* $1/T$, the thermodynamic parameters (*i.e.* enthalpy change ΔH, and entropy change ΔS) for the formation of the complexes were calculated. The resulting values are tabulated in Table 1.

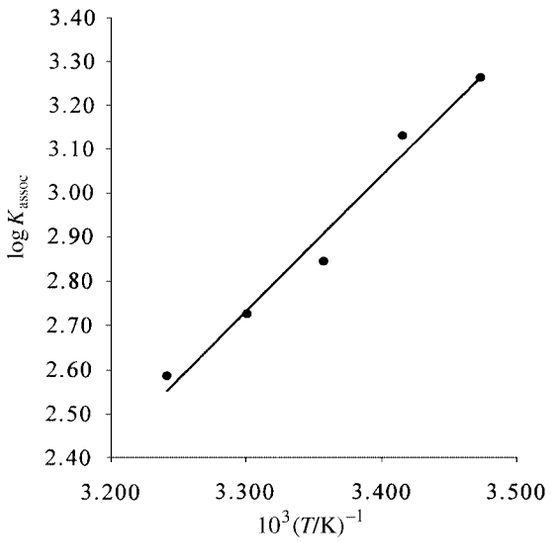


Fig. 2 Plot of log K *vs.* $1/T$ for the complexation of C_{60} and **4** in toluene solution.

Acknowledgements

This research was supported by the Natural Sciences and Research Council of Canada and the Department of Chemistry, Memorial University of Newfoundland. Ms Linda Thompson is thanked for her technical support and Dr Peter Tremaine for ongoing discussions.

References

1 J. L. Atwood, G. A. Koutsoantonis and C. L. Raston, *Nature*, 1994, **368**, 229. For more recent contributions see: L. R. MacGillivray and J. L. Atwood, *Nature*, 1997, **389**, 469; J. L. Atwood, L. J. Barbour, C. L. Raston and I. B. N. Sudria, *Angew. Chem.*, *Int. Ed. Engl.*, 1998, **37**, 981.
2 T. Suzuki, K. Nakashima and S. Shinkai, *Chem. Lett.*, 1994, 699.
3 For a recent bibliography see F. C. Tucci, D. M Rudkevich and J. Rebek, Jr., *J. Org. Chem.*, 1999, **64**, 4555 and references cited therein.
4 A. F. Danil de Namor, R. M. Cleverly and M. L. Zapata-Ormachea, *Chem. Rev.*, 1998, **98**, 2495.
5 S. Shinkai and A. Ikeda, *Gaz. Chim. Ital.*, 1997, **127**, 657.
6 P. E. Georghiou and Z.-P. Li, *Tetrahedron Lett.*, 1993, **34**, 2887.
7 P. E. Georghiou, M. Ashram, Z.-P. Li and S. Chaulk, *J. Org. Chem.*, 1995, **60**, 7284.
8 P. E. Georghiou, S. Mizyed and S. Chowdhury, *Tetrahedron Lett.*, 1999, **40**, 611.
9 D. J. Cram and J. M. Cram, *Container Molecules and Their Guests*, Royal Society of Chemistry, Cambridge, 1994.
10 W. Tao and M. Barra, *J. Chem. Soc.*, *Perkin Trans. 2*, 1998, 1957.
11 Y. Inoue, T. Hakushi, Y. Liu, L.-H. Tong, B.-J. Shen and D.-S. Jin, *J. Am. Chem. Soc.*, 1993, **115**, 457.
12 Y. Inoue, Y. Liu, L.-H. Tong, B.-J. Shen and D.-S. Jin, *J. Am. Chem. Soc.*, 1993, **115**, 10637.
13 A. Benesi and J. H. Hildebrand, *J. Am. Chem. Soc.*,1949, **71**, 2703.
14 A. Ikeda, Y. Suzuki, M. Yoshimura and S. Shinkai, *Tetrahedron*, 1998, **54**, 2497.
15 (*a*) G. D. Andreetti, R. Ungaro and A. Pochini, *J. Chem. Soc.*, *Chem. Commun.*, 1979, 1005; (*b*) M. Coruzzi, G. D. Andreetti, V. Bocchi and A. Pochini, *J. Chem. Soc.*, *Perkin Trans. 2*, 1982, 1133; (*c*) G. D. Andreetti, A. Pochini and R. Ungaro, *J. Chem. Soc.*, *Perkin Trans. 2*, 1983, 1773; (*d*) C. Rizzoli, G. D. Andreetti, R. Ungaro and A. Pochini, *J. Mol. Struct.*, 1982, **82**, 133.
16 S. Chowdhury, J. N. Bridson and P. E. Georghiou, unpublished results.
17 N. Sivaraman, R. Dhamodaran, I. Kaliappen, T. G. Srinivassan, P. R. Vasudeva Rao and C. K. Matthews, *J. Org. Chem.*, 1992, **57**, 6077.
18 T. Haino, M. Yanase and Y. Fukazawa, *Angew. Chem.*, *Int. Ed. Engl.*, 1997, **36**, 259.

19 T. M. Letcher, P. B. Crosby, U. Domanska, P. W. Fowler and A. C. Letcher, *S. Afr. J. Chem.*,1993, **46**, 41.
20 H. Matsubara, T. Shimora, A. Hasegawa, M. Semba, K. Asano and K. Yamamoto, *Chem. Lett.*, 1998, 1099.
21 H. Matsubara, A. Hasegawa, K. Shiwaku, K. Asano, M. Uno, S. Takahashi and K. Yamamoto, *Chem. Lett.*, 1998, 923.
22 T. Haino, M. Yanase and Y. Fukazawa, *Angew. Chem.*, *Int. Ed. Engl.*, 1998, **37**, 997.
23 L. J. Bauer and D. Gutsche, *J. Am. Chem. Soc.*,1985, **107**, 6063.
24 We are grateful to one of the referees of our original manuscript for making these suggestions.
25 M. Ashram, *Synthesis of calix[4]naphthalenes and their properties*, PhD Dissertation, Memorial University of Newfoundland, St. John's, Newfoundland, Canada, 1997.
26 R. C. Petersen, *J. Org. Chem.*, 1964, **29**, 3133. We acknowledge the referees who brought this paper to our attention.

Paper a907733b