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Cation–π complexes of a bowl-shaped polycyclic aromatic hydrocarbon

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ABSTRACT: Circumtrindene (**1**), a $C_{36}H_{12}$ geodesic polyarene that represents 60% of fullerene-C_{60}, forms cation–π complexes with both silver ion ($\mathbf{1} \cdot Ag^+$) and tetramethylammonium ion [$(Me)_4N^+ \cdot \mathbf{1}$] in chloroform solution at room temperature ($K_a > 20\ \mathrm{M}^{-1}$ for both cations). Preferential binding in the concave pocket of **1** is predicted by DFT calculations for both cations; however, this stereochemical assignment has not yet been confirmed experimentally. Copyright © 2004 John Wiley & Sons, Ltd.

KEYWORDS: geodesic polyarene; tetramethylammonium picrate; NMR titrations; host–guest complexes; supramolecular; concave π-surfaces; convex π-surfaces; DFT calculations

INTRODUCTION

Cation–π complexes of aromatic compounds (Fig. 1) have received an enormous level of attention in recent years, in part as a result of the role they are now believed to play in protein folding, neurological signaling, the functioning of certain gated ion channels and other diverse biological phenomena.[1] From much close scrutiny, there has emerged a general consensus that the degree to which electron deficient cations are attracted to the electron-rich faces of aromatic rings correlates with the electrostatic potentials of the π-systems.[2]

In the absence of desymmetrizing substituents, the two faces of a planar polyarene must be either homotopic or enantiotopic and thereby must have equivalent electrostatic potentials. In geodesic polyarenes such as circumtrindene (**1**,[3] Fig. 2), however, that symmetry is broken, and the electrostatic potentials of the two faces no longer remain the same. In principle, one surface must be more electron rich than the other. As we have reported some time ago,[4] it is the concave surface of such bowl-shaped polycyclic aromatic hydrocarbons (PAHs) that show the more negative electrostatic potential, and it follows, therefore, that cation–π complexation should be favored *inside* the bowl rather than outside, in the absence of overriding steric factors. Here we report the first experimental evidence for complexation of silver ion to a geodesic polyarene in solution and the first experimental evidence for complexation of tetramethylammonium ion [$(Me)_4N^+$] to a geodesic polyarene in solution, using circumtrindene (**1**) in both cases. DFT calculations predict preferential binding to the concave face of **1** (discussed below); however, our experimental data do not provide definitive evidence on this stereochemical point.

SILVER ION COMPLEXATION OF CIRCUMTRINDENE (1)

Among the monoatomic +1 ions, Ag(I) stands out as showing a particularly strong affinity for the electron-rich faces of aromatic hydrocarbons. Many x-ray crystal structures of PAHs complexed with silver perchlorate have been reported.[5] Silver ion coordination has also been exploited to generate ionic derivatives of PAHs in the gas phase that can be detected by electrospray mass spectrometry.[6] In solution, Ag(I) has been put to clever use as an ‘attractant’ to bring NMR shift reagents and PAHs into close proximity with one another.[7] In the absence of silver ions, lanthanide shift reagents do not form complexes with PAHs, so they have no influence on their NMR spectra. Silver ions alone likewise cause no significant changes in the NMR spectra of PAHs. When used together, however, lanthanide shift reagents are attracted to PAH · Ag(I) complexes, presumably through coordination of their tightly bound anionic ligands to the electron deficient silver, and the NMR spectra of the PAHs become significantly altered. We have used this method to monitor the cation–π interaction of silver ion with circumtrindene (**1**) as a function of concentrations of the partners.

Figure 3 shows the 400 MHz ^{1}H NMR spectrum of pure circumtrindene (**1**) in $CDCl_3$ at 30 °C. To this solution, a 1:1 mixture of Ag(fod) and $Yb(fod)_3$ was added in small portions while keeping the concentration

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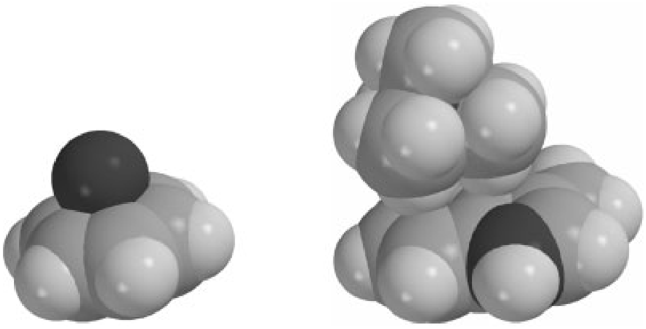

Figure 1. Cation–π complexes of silver ion with benzene (left) and of tetramethylammonium ion with the indole side-chain of tryptophan (right)

Figure 2. Three views of circumtrindene (**1**)

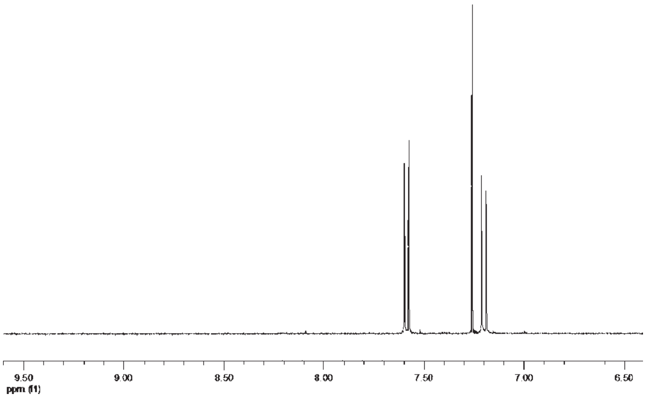

Figure 3. 400 MHz ^{1}H NMR spectrum of pure circumtrindene (**1**) in $CDCl_3$ at 30 °C

of **1** constant. After each addition, the ^{1}H NMR spectrum was recorded. Figure 4 shows the spectrum of **1** in $CDCl_3$ after a total of 5.0 equiv. each of Ag(fod) and $Yb(fod)_3$ had been added.

Clearly, both doublets in the ^{1}H NMR spectrum of **1** shift downfield in the presence of $Ag(fod) \cdot Yb(fod)_3$. The low-field doublet (7.58 ppm) shifts slightly more than the high-field doublet (7.19 ppm), but the difference in the behavior of the two signals is minor.

The data for the change in chemical shift (Δ) of the doublet at 7.19 ppm as a function of the concentration of $Ag(fod) \cdot Yb(fod)_3$ (Table 1) were used to generate the double reciprocal plot shown in Fig. 5. From the slope of the resulting straight line (correlation coefficient = 0.998), we derive an association constant $K_a = 30.2 \pm 0.1\,\text{M}^{-1}$ for the complexation of **1** with $Ag(fod) \cdot Yb(fod)_3$ at 30 °C.[8] We hasten to point out, however, that not every $\mathbf{1} \cdot Ag(I)$ complex is guaranteed to have a $Yb(fod)_3$ attached, which means that the value of $K_a = 30\,\text{M}^{-1}$ represents a *lower limit* for the association

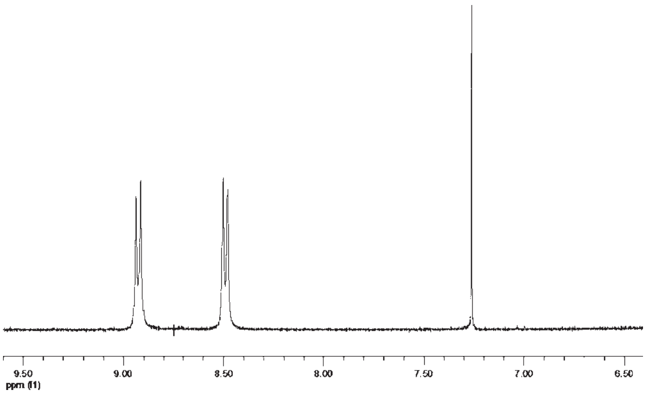

Figure 4. 400 MHz ^{1}H NMR spectrum of circumtrindene (**1**) in $CDCl_3$ at 30 °C with 5.0 equiv. each of Ag(fod) and $Yb(fod)_3$ added

Table 1. ^{1}H NMR titration of circumtrindene (**1**) in $CDCl_3$ at 30 °C with 1:1 Ag(fod):$Yb(fod)_3$[a]

$1/\Delta$ ($C_{36}H_{12}$)	$1/C$ [Ag(fod)]
4.25	250.43
2.40	119.25
1.82	83.48
1.39	61.08
1.16	45.53
1.03	36.83
0.87	29.12
0.76	23.63

[a] The concentration of circumtrindene was held constant and the change in chemical shift (Δ) of the circumtrindene doublet at 7.19 ppm was followed as 5.0 equiv. of $Ag(fod) \cdot Yb(fod)_3$ were added (see Figs 3 and 4).

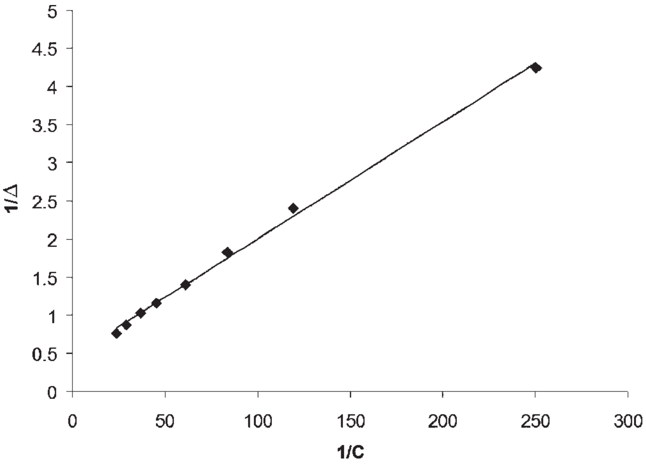

Figure 5. ^{1}H NMR titration of circumtrindene (**1**) in $CDCl_3$ at 30 °C with 5.0 equiv. of 1:1 Ag(fod)–$Yb(fod)_3$. Data taken from Table 1

constant of circumtrindene (**1**) with silver ion in chloroform solution. Notwithstanding this uncertainty with the quantitative analysis, our results provide undeniable evidence for the complexation of circumtrindene (**1**) with silver ion in chloroform solution.

Published quantitative data on the magnitude of silver cation–π complexation with aromatic hydrocarbons in solution remains sparse. Lhotak and Shinkai have reported association constants for the complexes of several calix[*n*]arenes with silver ion; however, they argue convincingly that most of the complexes they observe involve at least some interactions of the silver ion with electron pairs on oxygen substituents or with olefinic π-bonds in bridges used to form π-lined cages.[9] For two cases in which the silver appears to be genuinely complexed only to the π–faces of benzene rings, association constants of 17.8 and 14.1 M^{-1} were measured.[9] By comparison, circumtrindene (**1**) can be classified as a relatively good host for silver cation.

We have carried out DFT calculations on circumtrindene (**1**) and silver ion using Gaussian 03[10] [for the geometry optimizations, the guest was positioned some distance away from the circumtrindene and allowed to migrate to the nearest local minimum (*exo* or *endo*)] at the B3LYP/3–21G** level of theory; higher quality basis sets for silver are not yet available in Gaussian, unfortunately. As expected, complexation *inside* the bowl is favored over complexation on the convex surface (Fig. 6). The preference for *endo* binding over *exo* binding at this level of theory is 1.2 kcal mol^{-1} (1 kcal = 4.184 kJ). The complexation is strong in both cases: -57.8 and -56.6 kcal mol^{-1}, respectively, relative to the free partners, **1** and Ag^+. These are gas-phase calculations, of course, and binding is not expected to be so exothermic in solution with the counterion and Yb(fod)$_3$ lurking nearby.

As can be seen in Fig. 6, the silver in the *endo* complex sits deep in the $C_{36}H_{12}$ bowl. The interatomic distance from the silver to each of the six carbon atoms at the base of the bowl is ca 2.86 Å and to each of the next six carbon atoms up from the base is ca 3.02 Å. In the *exo* complex, the silver moves off-center toward one of the five-membered rings, according to these calculations. Numerous calculations on the complexation of other geodesic polyarenes with other monatomic ions and coordinated transition metals have been reported over the years, and the preference for *endo* vs *exo* binding appears to be system dependent.[11] On the experimental side, there is solid evidence that electrophilic metals can bind to the concave face of corannulene,[11f] a $C_{20}H_{10}$ geodesic polyarene, and that the concave surface of other hydrocarbon π-systems are attractive to electron deficient partners.[12] Nevertheless, despite the intuitive appeal of the 'catcher's mitt' complex pictured in Fig. 6, we reiterate that there is no experimental proof for the stereochemistry of the $\mathbf{1}\cdot\text{Ag}^+$ complex that we have observed by NMR spectroscopy.

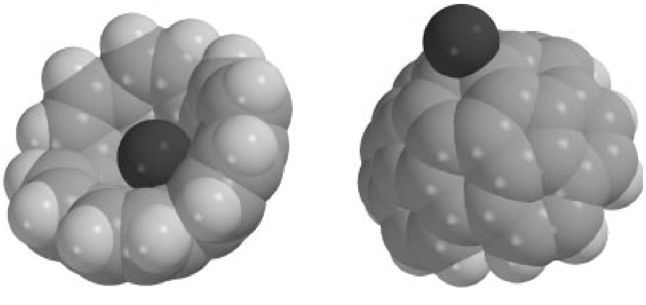

Figure 6. Cation–π complex of silver ion with the concave surface of circumtrindene (left) and with the convex surface of circumtrindene (right), both calculated at the B3LYP/3–21G** level of theory

TETRAMETHYLAMMONIUM ION COMPLEXATION OF CIRCUMTRINDENE (1)

The strength of a cation–π interaction in solution can depend strongly on the nature of the counterion and is generally greatest with an anion such as picrate, in which the negative charge is highly dispersed.[2a,b,e,f,13] To probe the ability of circumtrindene (**1**) to form a cation–π complex with tetramethylammonium ion [$(\text{Me})_4\text{N}^+$], therefore, we performed our experiments with tetramethylammonium picrate (TMAP). For these NMR titrations, the concentration of TMAP in $CDCl_3$ was held constant, and 25 equiv. of **1** were added in several portions. As **1** was added, the singlet at 3.45 ppm for the methyl hydrogens of the $(\text{Me})_4\text{N}^+$ shifted to *higher* field in the ^{1}H NMR spectrum (Table 2); hence the protons are *shielded* by the bowl. The double reciprocal plot generated from these data (Figure 7) also gives a straight line (correlation coefficient = 0.997), from which we derive an association constant $K_a = 23.8 \pm 2.3\ \text{M}^{-1}$ for the complexation of **1** with TMAP in chloroform at 30 °C.[8]

Roelens and co-workers have studied the cation–π complexes of TMAP with numerous cyclophanes and have report association constants in the range from 0 to

Table 2. ^{1}H NMR titration of tetramethylammonium picrate (TMAP) in $CDCl_3$ at 30 °C with 25 equiv. of circumtrindene (**1**)[a]

1/Δ (TMAP)	1/*C* [$C_{36}H_{12}$]
−111.11	737.74
−62.50	368.87
−40.00	245.91
−31.25	184.44
−24.39	147.55
−19.23	122.96
−18.52	105.39
−16.67	81.97

[a] The concentration of TMAP was held constant and the change in chemical shift (Δ) of the TMAP singlet at 3.45 ppm was followed as 25 equiv. of circumtrindene were added.

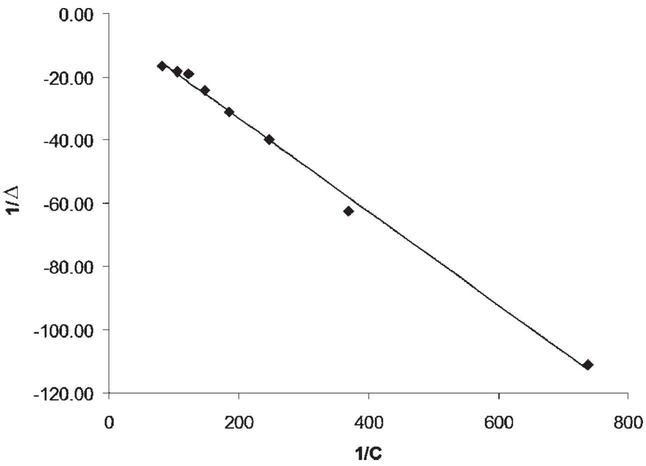

Figure 7. ^{1}H NMR titration of tetramethylammonium picrate (TMAP) in $CDCl_3$ at 30 °C with 25 equiv. of circumtridene (**1**). Data taken from Table 2

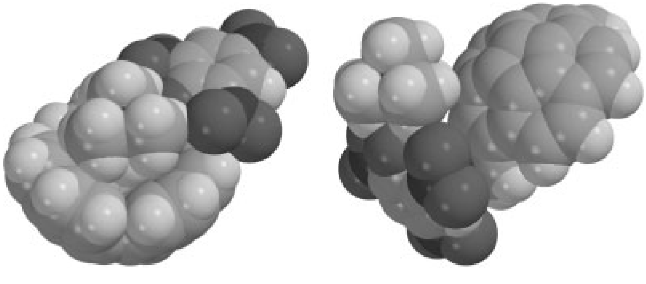

Figure 8. Cation–π complex of tetramethylammonium picrate (TMAP) with the concave surface of circumtrindene (left) and with the convex surface of circumtrindene (right), both calculated at the B3LYP/6–31G** level of theory

$29.7\,\text{M}^{-1}$ in chloroform.[2a,b,e] Calix[5]arenes with deep cavities and rigidifying bridges, on the other hand, can completely engulf the tetramethylammonium ion and force the picrate to interact through the wall of the host.[13b] With these preorganized π-lined cavities, association constants as large as $2200\,\text{M}^{-1}$ have been measured for TMAP in chloroform. The cavity of circumtrindene is certainly rigid, and its dimensions are about right to accommodate one methyl group of the $(Me)_4N^+$, but that leaves the nitrogen atom and the other methyl groups available for contact ion pairing with the picrate (Fig. 8), a situation that is known to reduce the strength of the cation–π interaction considerably.[14]

We carried out DFT calculations on circumtrindene (**1**) and TMAP (with the picrate counterion included) at the B3LYP/6–31G** level of theory using Spartan 02.[15] As with silver ion, complexation *inside* the bowl is favored over complexation on the convex surface (Fig. 8). The preference for *endo* over *exo* binding at this level of theory is $4.1\,\text{kcal mol}^{-1}$. The calculated binding energies for the two complexes, relative to **1** separated from the TMAP ion pair, are -8.3 and $-4.2\,\text{kcal mol}^{-1}$, respectively.

CONCLUSIONS

Solid experimental evidence has now established that circumtrindene (**1**) forms a cation–π complex not only with Ag^+ but also with $(Me)_4N^+$ in chloroform solution at 30 °C. Association constants $K_a > 20\,\text{M}^{-1}$ were found for both cations by NMR titration studies. DFT calculations point to preferential binding of both cations on the concave surface of **1**, although experimental confirmation of this stereochemical assignment is not currently available.

Acknowledgement

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