JACS
JOURNAL OF THE AMERICAN CHEMICAL SOCIETY
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Ion-Regulated Allosteric Binding of Fullerenes (C_{60} and C_{70}) by Tetrathiafulvalene-Calix[4]pyrroles

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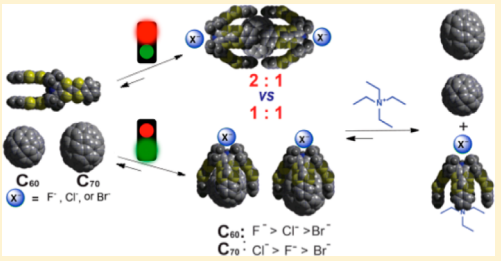
Supporting Information

ABSTRACT: The effect of ionic species on the binding of fullerenes (C_{60} and C_{70}) by tetrathiafulvalene-calix[4]pyrrole (TTF-C4P) receptors and the nature of the resulting supramolecular complexes (TTF-C4P + fullerene + halide anion + tetraalkylammonium cation) was studied in the solid state through single crystal X-ray diffraction methods and in dichloromethane solution by means of continuous variation plots and UV−vis spectroscopic titrations. These analyses revealed a 1:1 stoichiometry between the anion-bound TTF-C4Ps and the complexed fullerenes. The latter guests are bound within the bowl-like cup of the C4P in a ball-and-socket binding mode. The interactions between the TTF-C4P receptors and the fullerene guests are highly influenced by both the nature of halide anions and their counter tetraalkylammonium cations. Three halides (F^-, Cl^-, and Br^-) were studied. All three potentiate the binding of the two test fullerenes by inducing a conformational change from the 1,3-alternate to the cone conformer of the TTF-C4Ps, thus acting as positive heterotropic allosteric effectors. For a particular halide anion, the choice of tetraalkylammonium salts serves to modulate the strength of the TTF-C4P-fullerene host−guest binding interactions and, in conjunction with variations in the halide anion, can be exploited to alter the inherent selectivity of the host for a given fullerene. Differences in binding are reflected in the excited state optical properties. Overall, the present four-component system provides an illustration of how host−guest binding events involving appropriately designed artificial receptors can be fine-tuned via the addition of simple ionic species as allosteric modulators.



INTRODUCTION

Allosteric regulation by cofactors, either positive or negative, plays an essential role in modulating a broad range of biological processes.[1−3] Considerable effort therefore continues to be devoted to understanding and interpreting the effects of various cofactors that can control cooperative binding events.[3,4] Among these are ionic species, including relatively simple anions and cations. Depending on the particular situation, these charged species can influence the sites of biological action and either enhance or obstruct the binding while likewise reducing or promoting the reactivity of specific guest species.[3,5] Consequently, the design and study of artificial systems that display allosteric binding behavior regulated by small charged species is of inherent interest.[6−19] Not only can such systems help provide a better fundamental understanding of molecular recognition processes, they might also serve as a basis for preparing functional materials whose properties can be fine-tuned as the result of controlling cooperative binding interactions.

Recently, we reported the reversible supramolecular electron transfer (ET) between tetrathiafulvalene (TTF)-functionalized calix[4]pyrrole (C4P) **1** and dicationic bisimidazoliumquinone (BIQ^{2+}) salts (e.g., **3**) and showed that it could be controlled by the external addition of tetraalkylammonium-anion pairs (Figure 1).[20] In this system, coordinating anions (X^- = Cl^-, Br^-, or $MeSO_4^-$) were found to promote the forward electron transfer from **1** to **3** as the result of stabilizing supramolecular capsule-like ensembles of the type $[\mathbf{1}_2\cdot\mathbf{3}]\cdot 2X^-$ as stable ET intermediates. In contrast, smaller tetraalkylammonium cation salts, including tetraethylammonium halides, were found to compete with **3** for the C4P bowl of **1**, thus promoting inverse electron transfer. These findings were subsequently extended to include $[Li@C_{60}]^+$ as the electron acceptor.[21] In this case, a 1:1 binding stoichiometry between the electron rich TTF-C4P host **1** and the electron deficient fullerene acceptor was inferred. In earlier studies involving the TTF-C4P **1** and C_{60}, a 2:1

Received: May 1, 2014
Published: June 26, 2014

   dx.doi.org/10.1021/ja504077f | J. Am. Chem. Soc. 2014, 136, 10410−10417

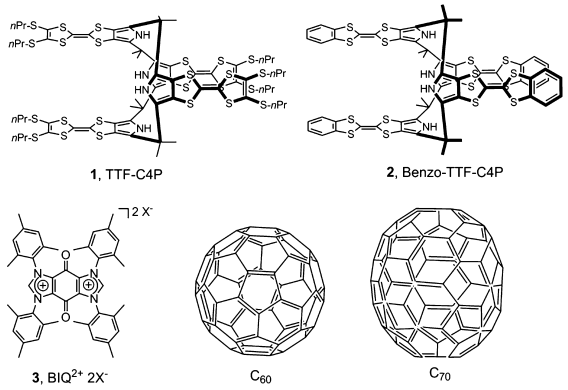


Figure 1. Structural formulas of tetrathiafulvalene-calix[4]pyrroles (TTF-C4Ps, **1** and **2**), bisimidazoliumquinone (BIQ^{2+}, **3**), C_{60}, and C_{70}.

receptor-guest binding stoichiometry was suggested.[22,23] The present study was undertaken in an effort to resolve what appears to be a conflict between these two proposed fullerene binding stoichiometries (i.e., 1:1 vs 2:1).

More broadly, the finding that certain coordinating anions and cations have opposing effects on a supramolecular thermal electron transfer process prompted us to investigate in-depth the effects of halide anions (F^-, Cl^-, and Br^-) and tetraalkylammonium cations (tetraethylammonium (TEA^+), tetrabutylammonium (TBA^+), and tetrahexylammonium (THA^+)) on the binding of fullerenes (C_{60} and C_{70}) by the TTF-calix[4]pyrrole **1** and its recently prepared benzo-annulated analogue **2** (collectively referred to as TTF-C4Ps), shown in Figure 1.[24] Because its interactions with fullerenes have not previously been studied, most emphasis will be placed on receptor system **2**. As implied above, a specific goal was to determine whether a 1:1 or 2:1 receptor-fullerene stoichiometry best represents the binding interactions involving both TTF-C4Ps and C_{60} or C_{70} under most conditions of analysis.

RESULTS AND DISCUSSION

As detailed in this report, the nature of both anions and cations can have a profound influence on the fullerene-binding properties of **1** and **2**. Specifically, we demonstrate how the intrinsic binding affinity of these receptors toward C_{60} and C_{70} can be modulated via the choice of the coordinating anion, viz. F^-, Cl^-, and Br^-. All three of these anions bind to **1** and **2** and stabilize the cone form of the calix[4]pyrrole. Thus, all three act as positive heterotropic allosteric regulators for the complexation of C_{60} and C_{70} by **1** and **2**. However, the specific choice of anion has a strong effect on the thermodynamic stabilities of the resulting supramolecular assemblies, as inferred from the fullerene binding constants recorded in dichloromethane solution. In fact, the selectivity of receptor **2**, i.e., favoring C_{60} or C_{70}, was found to be a function of the halide anion used to stabilize the cone conformer of the TTF-C4Ps. Moreover, in analogy to what was seen in the case of **1** and BIQ^{2+},[20] the nature of the tetraalkylammonium countercation has a strong effect on the binding of C_{60} and C_{70} in dichloromethane solution. In particular, smaller cations, such as TEA^+, compete with the fullerenes for the TTF-C4P cavity. They thus act as effective negative allosteric regulators. The net result is a level recognition complexity that is not generally seen for simple artificial fullerene receptors. We have also found that under most conditions of analysis a 1:1 binding stoichiometry, rather than the 2:1 ratio proposed earlier[22,23] for **1** and C_{60}, best

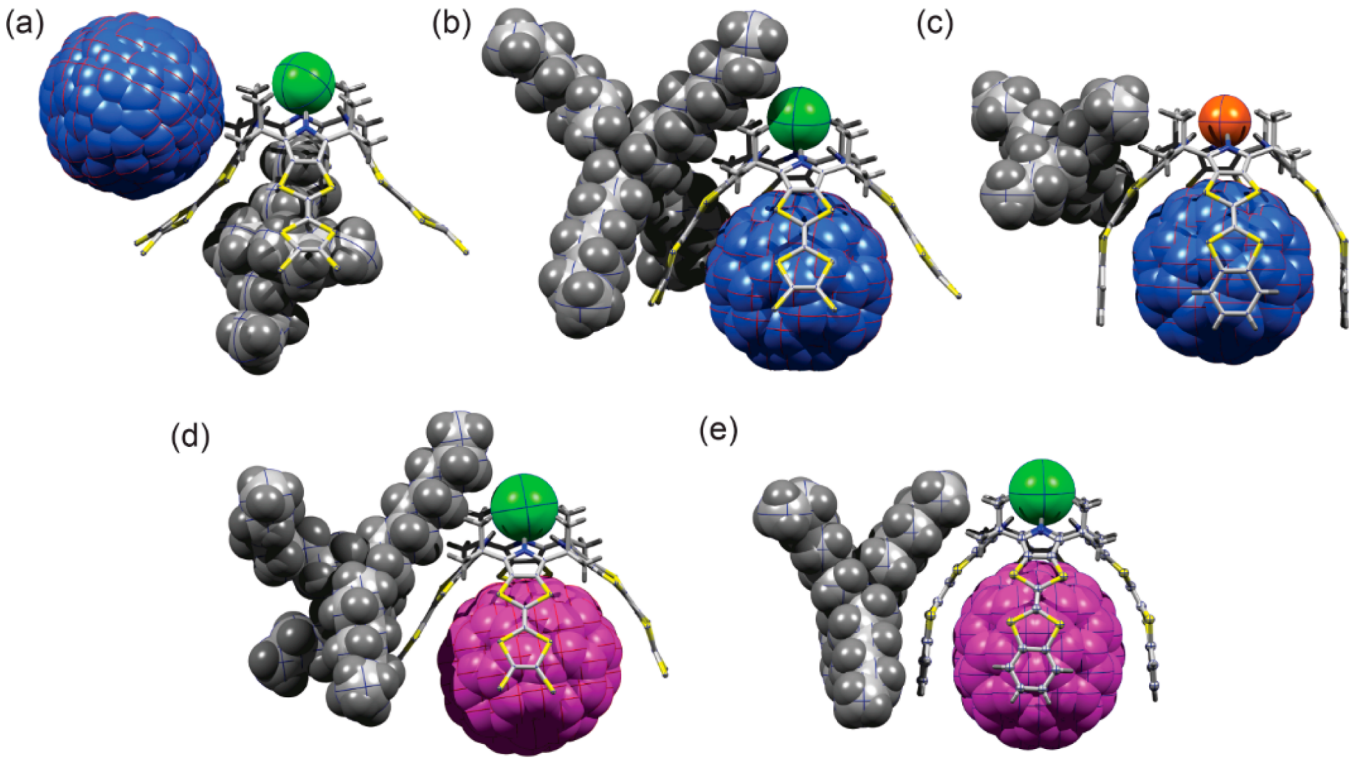


Figure 2. X-ray crystallographic analyses of (a) $(TBA)_6[(\mathbf{1}\cdot Cl)_6(C_{60})_8(toluene)_5]$,[22] (b) $(TOA)[C_{60} \subset (\mathbf{1}\cdot Cl)]$, (c) $(TBA)[C_{60} \subset (\mathbf{2}\cdot F)]$, (d) $(TOA)[C_{70} \subset (\mathbf{1}\cdot Cl)]$, and (e) $(THA)[C_{70} \subset (\mathbf{2}\cdot Cl)]$. For clarity, C_{60} and C_{70} are depicted as blue and purple space filling models, respectively, and the propyl groups on the TTF-C4P **1** are not shown.

dx.doi.org/10.1021/ja504077f | J. Am. Chem. Soc. 2014, 136, 10410−10417

describes the interactions between the two TTF-C4Ps and the two fullerenes of this study.

X-ray Crystallographic Analyses: Effects of Tetraalkylammonium Cations on Solid-State Structures. In our previous study involving the anion-triggered binding of C_{60} by **1**,[22] TBACl was used as the source of chloride. Its presence was required for effective fullerene binding. This was ascribed to it acting as an activating reagent that served to switch the TTF-C4P framework from the "inactive" 1,3-alternate conformation (with little or no appreciable fullerene affinity) to the corresponding cone conformer that possesses a hollow, bowl-like cavity ostensibly large enough to interact with the fullerene guest. However, in spite of the expectation that the C_{60} guest would be bound in this "bowl," an X-ray crystallographic analysis of single crystals obtained from a mixture of TBACl, receptor **1**, and C_{60} in toluene[22] revealed a complex multicomponent host–guest ensemble $(TBA)_6[(\mathbf{1}\cdot Cl)_6(C_{60})_8(toluene)_5]$ in the solid state. In this structure (cf. Figure 2a), a TBA^+ cation was found to occupy the internal cavity of **1**, rather than C_{60}. Furthermore, a rather unusual 3:4 stoichiometry between **1** and C_{60} was observed in the crystal as inferred from the structural analysis. In follow-up studies, it was determined that TBA^+ would bind to **1**·Cl in a 1:1 fashion with a binding constant (K_a) of 7400 M^{-1} in $CDCl_3$ as inferred from ^1H NMR spectroscopic analyses.[23] However, it was only in the context of our subsequent studies of **1** and BIQ^{2+},[20] as well as **1** and $Li@C_{60}^+$,[21] that we came to appreciate that smaller electron-deficient substrates, including smaller tetraalkylammonium cations, could compete with larger ones, such as BIQ^{2+} and $Li@C_{60}^+$ for the TTF-C4P cavity. To the extent this competition proved general, it would not only explain the unexpected structural result obtained in the context of our initial studies of the interactions between TTF-C4P **1** and C_{60}, but it would also highlight tetraalkylammonium cations as allosteric regulators that could function separately from, or in conjunction with, various halide anions.

As a first test of whether tetraalkylammonium cations and fullerenes might compete under conditions of single crystal formation, cocrystallization experiments involving **1** and C_{60} were carried out in the presence of tetraoctylammonium chloride (TOACl) rather than TBACl. The rationale behind this experiment is that the relatively large TOA^+ cation would not bind well within the concave cavity of **1** and thus not compete with the fullerene. Diffraction grade single crystals of this mixture were grown by allowing *n*-pentane to diffuse into a dichloromethane solution consisting of an equimolar mixture of the TTF-C4P **1**, fullerene, and TOACl. The resulting structure, shown in Figure 2b, revealed a chloride bound bowl-shaped TTF-C4P **1** that acts as a receptor to encapsulate the fullerene C_{60} within its cavity in the solid state. The complex, $(TOA)[C_{60} \subset (\mathbf{1}\cdot Cl)]$, stands in marked contrast to what was found for the corresponding TBA^+ system (vide supra). Moreover, a 1:1:1:1 stoichiometry between C_{60}, **1**, the chloride anion, and the TOA^+ cation (bound on the surface of receptor **1**) was found. As is expected for an anion-bound calix[4]-pyrrole, receptor **1** adopts a cone-like conformation wherein the four pyrrollic protons participate in concerted hydrogen bonding interactions with the chloride anion (N–H···Cl: 3.22–3.24 Å). Complementary electronic donor–acceptor interactions between the concave electron-rich π surface of **1** and the convex electron-deficient π surface of C_{60} were also seen. The net result is that the fullerene is bound in a ball-and-socket binding fashion.

In an effort to confirm and generalize these findings, further cocrystallization experiments were carried out using various combinations of **1**, **2**, C_{60}, C_{70}, and tetraalkylammonium salts of chloride, fluoride, and bromide. As the result of these efforts, diffraction-quality single crystals of three supramolecular host–guest complexes, namely, $(TBA)[C_{60} \subset (\mathbf{2}\cdot F)]$, $(TOA)[C_{70} \subset (\mathbf{1}\cdot Cl)]$, and $(THA)[C_{70} \subset (\mathbf{2}\cdot Cl)]$ were obtained. As can be seen from an inspection of Figure 2c, the use of TBAF in conjunction with **2** and C_{60} led to a structure analogous to that seen with TOACl (Figure 2b), wherein the fluoride-bound cone conformation of the receptor encapsulates the spherical fullerene in a 1:1 fashion (**2** to C_{60}). In contrast to what was seen in the initial study of receptor **1** (Figure 2a), the TBA^+ is located outside the cavity. This difference could reflect the fact that the benzannulated TTF moieties in receptor **2** are larger than those in **1** and relatively better able to embrace a spherical substrate.

Structural analysis of single crystals obtained from cocrystallization experiments involving the larger, oval-shaped C_{70} and receptors **1** and **2** revealed an encapsulation of C_{70} inside the internal cavities of the chloride-bound forms in both case (cf. Figure 2d,e). While a 1:1 receptor-fullerene stoichiometry was observed in both cases, a significant difference in the orientation of the bound ellipsoidal C_{70} was observed in the two structures. Whereas in the case of **1** a side-on conformation with respect to the imaginary C_4 axis of the cone-shaped calix[4]pyrrole framework is seen, with **2** the C_{70} is bound in an end-on orientation. These differences are thought to reflect the specific nature of the concave π-surfaces present in **1** and **2**, which differ in size, shape, and inherent flexibility.

Small differences between receptors **1** and **2** notwithstanding, on the basis of these new structural findings we conclude that encapsulation with a 1:1 receptor-fullerene stoichiometry will dominate for the halide bound forms under most crystallization conditions in the absence of a strongly competing counter-cation. Although the observed solid-state assembly may not necessarily reflect the most stable complex in solution, these results led us to reevaluate the 2:1 (**1**:C_{60}) stoichiometry that was initially proposed to be operative under conditions of solution phase binding in dichloromethane.[22]

Solution-State Stoichiometry Determinations via Continuous Variation Analysis. The 2:1 (**1**:C_{60}) binding stoichiometry that was originally proposed was based in large measure on so-called continuous variation analyses (also known as Job plots). For a well-behaved equilibrium involving the interaction between two components in solution, such analyses can serve as an informative tool to determine the stoichiometry of the host–guest binding event. However, mixtures of TTF-C4Ps, fullerenes, and tetraalkylammonium halide salts contain more than two interacting species. Artifacts are thus possible. This is particularly true if the tetraalkylammonium cations are acting as negative allosteric regulators by competing for the bowl-like fullerene binding site. The Job plot analyses for the system as originally reported (i.e., **1**, C_{60}, and TBACl) were carried out by mixing a series of two dichloromethane solutions, one of $[C_{60}]$ and the other [**1** + TBACl], in different ratios while maintaining constant total concentration of **1** and C_{60}. This produced Job plots that were interpreted in terms of a 2:1 receptor-fullerene stoichiometry. Unfortunately, this initial experimental approach failed to hold constant the concentration of TBACl throughout the study. Thus, the analyses did not account for the potentially competing role played by the tetraalkylammonium cation. To control for the potential

dx.doi.org/10.1021/ja504077f | J. Am. Chem. Soc. 2014, 136, 10410–10417

systematic error associated with our initial study, we have repeated our variation analyses while maintaining the concentration of TBACl constant during the entire spectral titration. Dichloromethane was used as the solvent, as it was in the original study. Under these conditions, the intensity of the charge-transfer (CT) absorbance feature associated with the formation of a TTF-C4P-fullerene complex reached to maxima when the molar faction of $[C_{60}]/[\mathbf{1} + C_{60}]$ is close to 0.5, as would be expected for a 1:1 binding stoichiometry (cf. Figure 3a). In addition, Job plot analyses of mixtures of **2**, TBACl, and

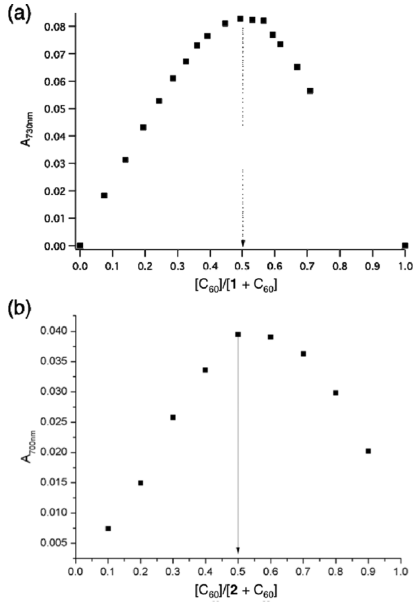


Figure 3. Continuous variation plot for the dichloromethane mixture of (a) **1** and C_{60} ($[\mathbf{1}+C_{60}] = 100\ \mu M$) in the presence of TBACl (500 μM) with the absorbance intensity ($\lambda = 730$ nm) plotted against molar fraction and (b) **2** and C_{60} ($[\mathbf{2}+C_{60}] = 50\ \mu M$) in the presence of TBACl (250 μM) with the absorbance intensity ($\lambda = 700$ nm) plotted against molar fraction. Both Job plots have maxima centered at 0.50, as would be expected for a 1:1 binding stoichiometry between the receptor in question and C_{60}.

either C_{60} or C_{70} were also consistent with a 1:1 receptor-fullerene binding stoichiometry (cf. Figure 3b). These observations are in agreement with the 1:1 encapsulation behavior seen in the solid state. We thus conclude that our earlier report[22] of 2:1 binding stoichiometry was in error and that, as inferred upon using $[Li@C_{60}]^+$ as a guest,[21] a 1:1 stoichiometry is a more accurate representation of the binding of fullerene into the cavity of the present set of TTF-C4P receptors.

We trace our improper stoichiometric assignment, namely, the suggestion of dominant 2:1 complex formation, to the use of Job's method of continuous variation to analyze a multicomponent equilibrium without setting conditions that reduce the complexity to the point where there are in effect only two interacting species in solution. The consequences of this oversimplification were exacerbated by using a plotting method that failed to account for the formation of complexes of TTF-C4P involving competing tetralkylammonium cations, rather than fullerenes. The need to control the conditions of analysis to account for competition, as well as the benefits of simplifying the effective equilibrium process, are important caveats associated with the use of Job's method that we believe should be considered in the study of complex mixtures to avoid introducing systematic errors.

We also studied the effect the ratio of TBACl to **1** had on the binding of C_{60} to **1** in dichloromethane as part of our detailed solution phase analyses. Toward this end, we varied the relative amount of TBACl from 1 to 50 equiv compared to the concentration of **1** and carried out UV−vis titrations and Job plot analyses to determine the extent of fullerene binding. As seen in the Supporting Information (Figure S6), a maximum binding between **1** and C_{60} is reached when TBACl is at approximately 5 equiv to **1**. The observed affinity did not change appreciatively when more than 5 equiv was present. These observations indicate that at least 5 equiv of TBACl are needed to ensure efficient conversion of the 1,3-alternate conformation to the cone conformation required for fullerene binding. In all cases, Job plot maxima were observed at a molar ratio of 0.5, thus providing further support for the proposed 1:1 TTF-C4P:fullerene binding stoichiometries.

Effect of Halide Anions on the Fullerene-Binding Affinities of TTF-C4Ps. In order to investigate whether the specific coordinating anion plays a central role in regulating the supramolecular interactions between TTF-C4Ps and fullerenes, a series of UV−vis photometric titrations were carried out. In these experiments, the countercation, TBA^+, was held constant and the K_a values corresponding to the interaction of receptors **1** and **2** with C_{60} and C_{70} were determined in the presence of three different halide salts, namely, TBAF, TBACl, or TBABr. These titrations were carried out in dichloromethane to allow comparisons with earlier results and to ensure the solubility of all components. The actual experiments were formally divided into two sets, which differed in terms of the titrating and titrated solutions. The first set of experiments involved adding increasing quantities of the fullerene in question to a solution containing either receptor **1** or **2** at an initial concentration of 10 μM in the presence of 10 equiv of TBAX (X = F^-, Cl^-, and Br^-). These are referred to as "normal titrations." In the other set, referred to as "inverse titrations," aliquots of the receptor, either **1** or **2**, were titrated into solutions of fullerenes (20 μM) containing 10 equiv of TBAX.

The two titration approaches were designed to evaluate different aspects of the competitive equilibrium. In the normal titration the receptors are already in equilibrium with the TBA^+ salts and, therefore, it was expected that some TBA^+ would already be bound within the cavity of the cone conformer of **1** or **2**. When a fullerene is titrated into such solutions, it must compete with the already complexed TBA^+ cation, which initially is in high excess compared to the added fullerene. When using this method, the only parameter changed is the ratio of fullerene to receptor in solution. However, in the inverse titrations aliquots of the receptors were added to solutions containing TBAX and fullerene. In this case, upon addition of the receptor to solution, the ratio of receptor:fullerene as well as the ratio of receptor:TBAX are both changing. Therefore, two parameters are constantly changing during the titration, rather than one parameter as is seen in the normal titration method. On account of these differences in titration methods, the K_a values will vary depending on whether they were recorded using the normal or the inverse titration method where the normal titration method better reflects the binding affinity since only one parameter is changed; however, in both cases the competition between fullerene and TBA^+ for the cavity exists.

It is also to be noted that only when the fullerene is successfully bound within the TTF-C4P cavity is a CT complex formed and the corresponding spectral features observed. Because of this, the change in intensity of the CT band (λ_{max} = 730 nm for **1** and 700 nm for **2**) could be monitored as a function of concentration of the titrating component. In all cases, the titrating solutions contained the titrant at its initial concentration so as to avoid dilution effects. Standard curve fitting then allowed effective binding constants (K_a) to be determined. These are tabulated in Table 1.

Table 1. Effective Binding Constants (K_a, M^{-1}) Corresponding to the Interaction between TTF-C4P 2 and C_{60} or C_{70} as Determined in the Presence of 10 mol equiv of the TBA Salts of Selected Anions in Dichloromethane[a]

compound		C_{60}	C_{70}
TBAF	normal	2 500 000	210 000
	inverse	8 100 000	830 000
TBACl	normal	640 000	1 400 000
	inverse	390 000	3 300 000
TBABr	normal	450 000	17 000
	inverse	28 000	17 000

[a]All K_a values were obtained from UV−vis spectrophotometric titration experiments carried out at 296 K. The binding stoichiometry was assigned as 1:1 on the basis of the continuous variation (Job) plots. Further details are given in the text. The estimated errors are ≤15%.

Although all three halide anions (F^-, Cl^-, and Br^-) are able to bind to **1** and **2** and to induce a conformational change from an inactive 1,3-alternate to an active cone conformer capable of encapsulating a fullerene, the thermodynamic stabilities of the resulting supramolecular ensembles [fullerene ⊂ (**1**·X)]$^-$ and [fullerene ⊂ (**2**·X)]$^-$ at constant TBA^+ concentration are strongly influenced by the choice of the coordinated halide anion. In the case of receptor **1** with C_{60}, the fluoride anion gave the highest C_{60} binding affinity (1 800 000 M^{-1}) followed by chloride (110 000 M^{-1}) and bromide (34 000 M^{-1}), as determined using the inverse titration method. Thus, the smallest anion (fluoride) produces the largest C_{60} binding affinity and the largest anion (bromide) gives rise to the smallest binding affinity. This correlates well with the basicity of the anions. Specifically, the most basic halide anion, fluoride, binds most effectively to the calix[4]pyrrole NH protons. This trend was also seen in the case of receptor **2**, as reflected in the magnitude of the K_a values measured by both normal and inverse titrations; again, the highest C_{60} affinity was seen for the fluoride anion, followed by chloride and bromide (Table 1). However, in the case of **2**, when the fullerene was changed from C_{60} to C_{70}, the highest K_a values are seen for the chloride anion, with the use of either fluoride or bromide giving rise to substantially lower binding affinities. As a consequence of this difference in relative affinities, receptor **2** binds C_{60} more strongly than C_{70} in the presence of fluoride or bromide. In contrast, it binds C_{70} more strongly than C_{60} in the presence of chloride. On this basis, we conclude that the halide anions act as positive heterotopic allosteric effectors for fullerene binding and that they are capable of modulating the binding strength and altering the relative selectivity of receptor **2**. To the best of our knowledge, such switching has not been previously observed for artificial fullerene receptors.

In an effort to understand the above anion-dependent fullerene binding effects, the affinities of the halide anions for receptor **2** were evaluated in the absence of fullerene. On the basis of separate UV−vis spectroscopic titrations carried out in dichloromethane in the presence of TBAF, TBACl, and TBABr, it was found that fluoride binds to receptor **2** with highest affinity (K_a = 2.4 × 10^7 M^{-1}), followed by chloride (1.6 × 10^6 M^{-1}), and bromide (1.5 × 10^4 M^{-1}). This affinity order, corresponding to the formation of a two-component ensemble (**2**·X^-), is in full agreement with what has previously been observed for simple unfunctionalized calix[4]pyrroles.[25] These affinities also mirror those seen for the formation of the three-component supramolecular assemblies involving C_{60} (i.e., [C_{60} ⊂ (**1**·X)]$^-$ and [C_{60} ⊂ (**2**·X)]$^-$). However, they do not conform to what was found in the case of C_{70} complexation with **2**. Thus, simple anion affinity differences do not suffice to account for the changes in fullerene selectivity noted above.

We rationalize the anion dependent change in fullerene binding behavior on steric grounds. Specifically, we propose that complexation of halide anion by the calix[4]pyrrole NH protons affects the size and shape of the resulting bowl-shaped cavity of receptor **2** and this translates into differences in fullerene binding affinity. Support for this supposition comes from a comparison of the X-ray structures of [C_{60} ⊂ (**2**·Cl)]$^-$ and [C_{70} ⊂ (**2**·F)]$^-$. In fact, the smaller F^- anion is held above the calix[4]pyrrole cone at shorter hydrogen bond distances than the chloride anion (2.72 Å for N−H···F vs 3.25−3.27 Å for N−H···Cl). This tighter geometric binding enforces a significantly wider bite angle in the case of fluoride than chloride (∠120° for NH···F···NH vs ∠94° for NH···Cl···NH). We thus propose that, as compared to fluoride, chloride binding serves to generate a cavity that is more suitable for encapsulating the larger, ellipsoid-shaped C_{70}.

Assessing the Effects of the Tetraalkylammonium Cation on Fullerene-Binding. As noted above, there is a sharp contrast in the solid-state structures for $(TBA)_6$[(**1**·Cl)$_6$(C_{60})$_8$(toluene)$_5$] and both (TOA)[C_{60} ⊂ (**1**·Cl)] and (TBA)[C_{60} ⊂ (**2**·F)] in terms of the encapsulated species. This observation prompted us to investigate the effects of various tetraalkylammonium (TAA) cations on the supramolecular interactions between the TTF-C4Ps and the fullerenes C_{60} and C_{70} in dichloromethane solution. In order to probe these effects, if any, we conducted a series of UV−vis spectral titrations using the chloride anion salts of the THA^+, TBA^+, and TEA^+ cations. This choice was expected to allow us to probe the effect of cation size and charge density on fullerene binding while keeping the counteranion constant. Because higher affinities were expected, allowing differences to be more easily noted, this set of studies was carried out using receptor **2**.

A first set of titrations was carried out by adding aliquots of a concentrated dichloromethane solution of C_{60} (120 μM) into a dichloromethane solution of **2** (10 μM) containing 10 equiv of the corresponding tetraalkylammonium chloride (TAACl) with respect to **2**. This thus corresponds to a so-called normal titration. To avoid dilution effects, all titrating solutions contained the titrant at its initial concentration. In all cases, a color change from yellow to green, ascribed to CT interactions between **2** and C_{60}, was observed as the titrations progressed. However, at any given molar ratio the extent of color progression differed according to the salt employed, with the greatest changes being observed in the case of THACl. Plots of the associated changes in absorption intensity at 700 nm as a function of C_{60} concentration were then used to construct

dx.doi.org/10.1021/ja504077f | J. Am. Chem. Soc. 2014, 136, 10410−10417

binding isotherms (cf. Supporting Information). The resulting K_a values are plotted in Figure 4.

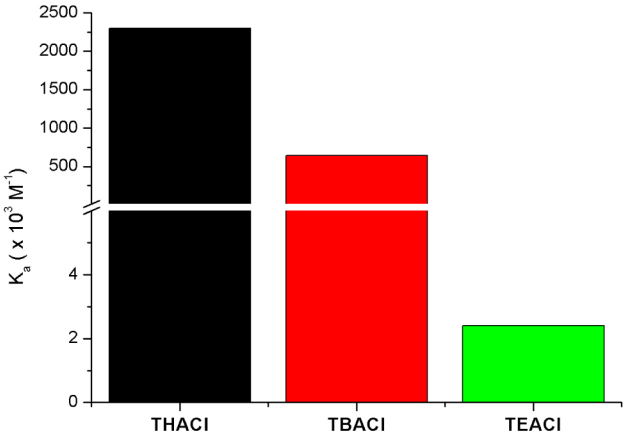


Figure 4. K_a values corresponding to the interaction of **2** and C_{60} as measured in dichloromethane solution in the presence of three different tetraalkylammonium (TAA^+) chloride salts, THACl, TBACl, and TEACl.

As can be seen from an inspection of Figure 4, the choice of the tetraalkylammonium cations has a profound effect on the K_a value representing the binding of C_{60} to receptor **2**. Specifically, for the same receptor, anion, and solvent, the fullerene affinity is increased by over four orders of magnitude when the chloride countercation was changed from TEA^+ to THA^+. On this basis, we conclude that the smaller and more positively charged cationic species acts as an efficient inhibitor for fullerene binding. This finding is fully consistent with the solid state structures obtained for a number of calix[4]pyrrole receptors, including **1** (cf. Figure 2a), as well as the conclusion that smaller TAA^+ cations, including the TBA^+ cation, can bind within the bowl-like cavity of a calix[4]pyrrole when it is locked in its cone conformation via anion binding. More broadly, these results serve to underscore the need to control the cation concentration (and its nature) rigorously in carrying out Job plots, as noted above.

In order to evaluate further the efficiency of the binding inhibition produced by the TEA^+ cation, fullerene displacement experiments were performed in the case of both C_{60} and C_{70}. Toward this end, increasing quantities of TEACl were titrated in separate experiments into dichloromethane solutions containing the three-component supramolecular assemblies (THA)[$C_{70} \subset$ (**1**·Cl)], (THA)[($C_{60} \subset$ (**1**·Cl)], (THA)[$C_{70} \subset$ (**2**·Cl)] and (THA)[$C_{60} \subset$ (**2**·Cl)]. The titrated solution containing the supramolecular triads underwent a color change that was exactly opposite to that observed during the course of the above titrations (i.e., the solution went from green to yellow). This color change, which was reflected in a decrease in spectral intensity for the CT band, was taken as evidence that the bound fullerene, either C_{60} or C_{70}, was being displaced by the TEA^+ cation.

Changes reflecting displacement of the fullerene and complexation of the TEA^+ cation were also evident from the ^1H NMR spectrum (400 MHz, room temperature) recorded in deuterated dichloromethane. The signal associated with the CH_2 protons in TEACl usually centered around δ 3.42 ppm was found to broaden and shift to δ 3.05 ppm when added to the supramolecular assembly (THA)[$C_{60} \subset$ (**2**·Cl)]. Spectral changes indicating encapsulation of TEA^+ inside the cavity of **2** were also seen during the addition of TEACl to a solution of **2** in dichloromethane in the absence of fullerene (Supporting Information). Such spectral shifts are analogous to those observed when the TEA^+ cation was used to displace the cationic electron acceptor, BIQ^{2+}, from **1** and are also seen in the case of TBA^+ binding within the cavity of **1**·Cl in chloroform in the absence of a competitive guest.[20,23] They thus provide support for a binding model wherein, after titration, the TEA^+ cation is complexed within the cavity of the cone conformer **2**·Cl, rather than bound outside the receptor via nonspecific electrostatic interactions.

Plots of the change in absorption intensity at 700 nm as a function of TEA^+ concentration were used to calculate the effective cation binding constants (K_{eff}) under the conditions of the displacement experiment. To do this, the titration curves were fitted to both a 1:1 binding and a competitive interaction model.[26] The 1:1 binding model involved treating the TEA^+ cation and the $[C_{60} \subset (\mathbf{2}\cdot Cl)]^-$ (or the $[C_{70} \subset (\mathbf{2}\cdot Cl)]^-$) anion as the interacting species and C_{60} (or C_{70}) and [TEA $\subset$ (**2**·Cl)] as the products without taking into account the competition between the TEA^+ and fullerene for the cavity of **2**·Cl. In contrast, the competitive interaction model involved obtaining an K_a value for the interaction of TEA^+ with $(\mathbf{2}\cdot Cl)^-$ (producing [TEA $\subset$ (**2**·Cl)]) by accounting mathematically for the binding equilibrium between $(\mathbf{2}\cdot Cl)^-$ + C_{60} and $[C_{60} \subset (\mathbf{2}\cdot Cl)]^-$. The first of these treatments revealed that the calculated TEA^+ binding constant (K_{eff} = 69 000 M^{-1}) measured in a dichloromethane solution of (THA)[$C_{60} \subset$ (**2**·Cl)] (consisting of 10 μM of THACl, 10 μM of C_{60} and 10 μM of **2**) is higher than the corresponding value for (THA)[$C_{70} \subset$ (**2**·Cl)] (K_{eff} = 38 000 M^{-1}) studied under identical conditions. This difference in K_{eff} values is consistent with the larger fullerene, C_{70}, being bound more effectively within the cavity of **2** than C_{60} under these conditions (i.e., where the Cl^- anion is used to stabilize the conformation of the calix[4]pyrrole). This conclusion is in agreement with what was inferred based on a direct analysis of the **2** + C_{60} and **2** + C_{70} binding interactions carried out using the less competitive TBA^+ cation (vide supra).

In contrast, the use of the competitive fitting model allowed a binding constant for the interaction of TEA^+ with the chloride anion-bound, cone form of receptor **2** to be calculated. The value obtained in this way, 420 000 M^{-1}, was found to be on the same order as the values obtained for the interaction of receptor **2** with C_{60} via either normal or inverse titrations carried out in the presence of TBACl (cf. Table 1). This provides further support for the conclusion that small cations can indeed compete with fullerenes for the C4P "bowl" and that failure to account for this fact, as was the case in our initial study,[22] can produce spurious results.

Photophysical Properties of the Supramolecular Assemblies. In order to obtain direct evidence for fullerene binding in solution, the excited state dynamics of supramolecular assemblies of generalized structure [fullerene $\subset$ (**1**·X)]$^-$ and [fullerene $\subset$ (**2**·X)]$^-$ were investigated by means of femtosecond transient absorption spectroscopy. Upon photoexcitation of **1** or **2** (100 μM) with either C_{60} or C_{70} (100 μM) in dichloromethane at the CT band (800 nm), the transient species of each complex revealed quite broad excited-state absorption (ESA) features in the visible and NIR spectral region (Figure 5a and Supporting Information). Characteristic spectral features, notably a prominent peak around 1080 nm ascribed to the one-electron reduced C_{60} radical anion,[22,27]

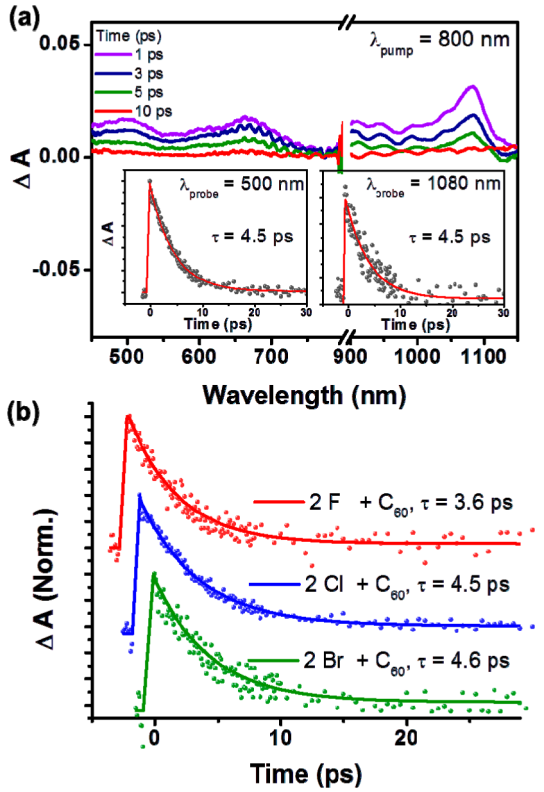


Figure 5. (a) Femtosecond transient absorption spectra of the supramolecular complex $[C_{60} \subset (\mathbf{2}\cdot X)]^-$ (TBA^+ countercation) in dichloromethane at 298 K. Insets show representative decay profiles at 500 and 1080 nm, respectively. (b) Representative decay profiles of $[C_{60} \subset (\mathbf{2}\cdot X)]^-$ at 500 nm in the presence of TBAF (red), TBACl (blue), and TBABr (green), respectively. The excitation wavelength was 800 nm in all cases.

were observed (cf. Supporting Information). This was taken as evidence that photoinduced electron transfer occurs within the ensemble, giving rise to a CT state. This state, more specifically the spectral features of the fullerene radical anion, appears instantaneously upon photoexcitation, an effect rationalized in terms of rapid electron transfer and formation of a charge separated (CS) state in the supramolecular C_{60}^- or C_{70}^- containing assemblies.

These photodynamic features are consistent with the X-ray crystal structures (Figure 2), which reveal strong donor/acceptor interactions between the TTF subunits of the receptor and the bound fullerene guests in the solid state. To the extent they are retained in solution, as proposed, these tight interactions are expected to translate into fast charge separation and recombination dynamics following photoirradiation. The charge recombination (CR) dynamics of various permutations of **1**, **2**, C_{60}, C_{70}, and the three standard test TBAX ($X^- = F^-$, Cl^-, and Br^-) salts were therefore analyzed via transient absorption spectroscopy (Figure 5). In all cases where the TBAX concentration (~100 μM) was sufficient to enforce fullerene complexation, CR occurred quickly (half-lives = 3.4–4.6 ps; Supporting Information Table S2).

The fast CR seen across the board is consistent with the suggestion that complexes of generalized structure $[\text{fullerene} \subset (\mathbf{1}\cdot X)]^-$ and $[\text{fullerene} \subset (\mathbf{2}\cdot X)]^-$ are being formed in solution under the conditions of analysis. In particular, it supports a model where the TTF-C4P·fullerene complexes of the present study are sustained via π–π interactions between the TTF subunits and the bound C_{60} or C_{70} moieties. Moreover, since relatively similar host–guest distances and donor/acceptor interactions are involved, similarly fast photoinduced electron transfer dynamics would be expected for all complexes. In general terms this is true. However, a small but discernible anion dependence is seen. Specifically for the supramolecular fullerene complexes of **1** and **2** (studied using C_{60} and both C_{60} and C_{70} as the guests, respectively), the time constants for the CR processes increase as the anion is changed from fluoride (3.4–3.6 ps) to either chloride or bromide (4.3–4.6 ps) (cf. Table S2 (SI) and Figures 5, S16, and S17 (SI)). Such affects are fully consistent with the small anion-induced variations in the solid state structures noted above. However, changes in the electronic character of the TTF units due to halide anion-dependent inductive effects may also be playing a role in modulating the observed CR rates.

Molecular Orbital Analyses. Quantum mechanical calculations based on the X-ray crystal structures involving receptors **1** and **2** with fullerenes C_{60} and C_{70} were carried out and support the observed fast CT processes seen in the TTF-C4P·fullerene complexes. Calculated molecular orbital (MO) structures (cf. Supporiting Information, Figures S18 and S19) revealed noticeable electron density on the TTF units of receptors **1** and **2**, as well as on the fullerene moieties, albeit in different orbitals. While the HOMO of the receptors are characterized by localized electron density on the TTF units, analysis of the LUMOs reveal electron densities localized on the C_{60} or C_{70} moieties (SI). These findings provide support for the notion that photoinduced CT from the TTF-C4P receptors to the fullerene guests will be facile and give rise to CS states containing a TTF cation radical and a fullerene anion radical, as is observed by experiment.

CONCLUSION

In summary, we have demonstrated that tetraalkylammonium halide salts act as allosteric effectors that can regulate the binding of fullerenes (C_{60} and C_{70}) to TTF-C4P receptors. This conclusion was reached on the basis of newly performed X-ray crystallographic and Job plot analyses, as well as supporting K_a value determinations and transient absorption spectral studies. On the basis of the present study, we conclude that under most conditions, a 1:1 binding stoichiometry best describes the TTF-C4P:fullerene interactions, rather than the binding 2:1 stoichiometry previously proposed.[22] Smaller tetraalkylammonium cations (TEA^+ and even TBA^+) can act as inhibitors of fullerene binding, meaning that erroneous conclusions can be drawn from continuous variation plots unless the conditions are set such that effectively only two interacting species undergo a change in concentration under the conditions of the analysis. It is suggested that such a need to control conditions should become a standard approach when using this method to analyze the solution phase stoichiometry of multicomponent supramolecular ensembles.

Although requiring an increased level of care for analysis, complex supramolecular systems, such as the ones described herein, are expected to further our understanding of how cooperative systems, both synthetic and natural, operate at the molecular level. In the present case, we have described a set of receptors, **1** and **2**, whose sensitivity and selectivity for a given target guest (C_{60} vs C_{70}) can be precisely tuned via the choice of anion and cation. This work thus sets the stage for even more elaborate studies where multicomponent allosteric binding effects are used to control the recognition features of

dx.doi.org/10.1021/ja504077f | J. Am. Chem. Soc. 2014, 136, 10410–10417

self-assembled materials, electron transfer ensembles, and species-selective chemosensor arrays.

■ ASSOCIATED CONTENT

Supporting Information

Experimental procedures, UV−vis spectroscopic data, binding isotherm analyses, ^{1}H and ^{13}C NMR spectra, and X-ray single crystallographic data. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This research was supported by the U.S. National Science Foundation (CHE-1057904), the Robert A. Welch Foundation (F-1018), the World Class University (WCU) (*R*32−2012−000−10217−0), and the Basic Science Research Program of the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT, and Future Planning (NRF-2013R1A1A1011508). The work at Yonsei University was supported by the Midcareer Researcher Program (2010−0029668) and a Global Frontier R&D Program (Center for Multiscale Energy Systems; 2012−8−2081) funded by the National Research Foundation under the Ministry of Science, ICT & Future Planning, Korea. The work at University of Southern Denmark was supported by the Villum Foundation, the Carlsberg Foundation, and the Danish Natural Science Research Council (FNU, Project 11−106744).

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