THE JOURNAL OF PHYSICAL CHEMISTRY B

Article

pubs.acs.org/JPCB

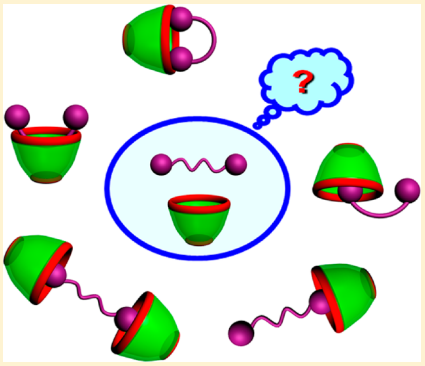
Binding Behaviors of *p*-Sulfonatocalix[4]arene with Gemini Guests

Hong-Xia Zhao, Dong-Sheng Guo, and Yu Liu*

Department of Chemistry, State Key Laboratory of Elemento-Organic Chemistry, Nankai University, Tianjin 300071, P. R. China

Supporting Information

ABSTRACT: A dozen of homoditopic cations, possessing different spacer lengths and rigidities, as well as sizes, shapes, and charges of terminal groups, were synthesized as candidate gemini guests for the complexation of *p*-sulfonatocalix[4]-arenes (SC4A). The 12 gemini guests are divided into five species according to the different terminal groups: imidazolium (G1−G3), pyridinium (G4−G6), quinolinium (G7), viologen (G8−G11), and 1,4-diazabicyclo[2.2.2]octane (DBO, G12). Their binding structures and stoichiometries with SC4A were examined by NMR spectroscopy, which is helpful to construct diverse highly ordered assemblies. The obtained results show that the length of the linkers, as well as the charge numbers on the end groups have a pronounced effect on the binding stoichiometry, whereas the size and shape of the terminal groups have no significant influence. Furthermore, both the stability constants and thermodynamic parameters of SC4A with the terminal subunits were determined by the isothermal titration calorimetry experiments, which are valuable to understand the binding behavior, giving quantitatively deep insight.

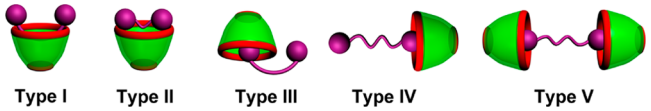


INTRODUCTION

p-Sulfonatocalix[*n*]arenes (SC*n*As, *n* = 4−8),[1] one fascinating family of water-soluble calixarene derivatives, have gained increasing attention in the past three decades.[2] Possessing three-dimensional, flexible, π-electron rich cavities, SC*n*As are promised to complex with numerous guest molecules, including inorganic cations,[3] organic ammonium cations,[4] pyridiniums/viologens,[5] neutral organic molecules,[6] dyes,[7] and biorelevant molecules.[8] In view of their robust inclusion properties, SC*n*As have been popularly applied in molecular recognition/sensing,[9] crystal engineering,[10] catalysis,[11] amphiphiles,[12] enzyme mimics/enzyme assays,[13] and pharmaceutical chemistry.[14] Recently, we and others have expanded the application of SC*n*As to the field of supramolecular polymers.[15] A series of electro-responsive (or light-) supramolecular polymers have been fabricated by our group utilizing the iterative complexation of homoditopic bis(*p*-sulfonatocalix[4]arenes) with homoditopic pyridinium and viologen guests.[15b,e] Subsequent to our works, Tian et al. reported a dual stimulus-responsive supramolecular polymer by employing a heteroditopic guest.[15c] Ditopic guests are commonly needed to achieve the highly ordered assemblies. However, there are several theoretically possible inclusion manners between SC*n*As and ditopic guests as shown in Scheme 1. The desired 1:2 type V manner is prerequisite for building supramolecular polymers. To our surprise, although a lot of effort has been devoted to the binding behaviors of SC*n*As with various organic cations,[8a−c,16] the inclusion phenomena of SC*n*As with ditopic guests have been paid much less attention,[17] despite some solid-state supramolecular structures.[18] With this regard, we wish to report herein that how SC*n*As include ditopic guests in aqueous solution. Prior to highly ordered assembly studies, it is crucial to get an in-depth knowledge on the binding behaviors of SC*n*As with various ditopic model guests.

Noticing that SC*n*As exhibit especially strong binding affinity and high molecular selectivity toward organic cations owing to the synergistic effect of additional anchoring points donated by sulfonate groups, we synthesized a dozen gemini organic cations as candidate guests, with different spacer lengths and rigidities, as well as sizes, shapes, and charges of terminal groups. Their binding structures and molar ratios with SC4A were examined by NMR spectroscopy, which was complementally discussed by isothermal titration calorimetry (ITC) results.

Scheme 1. Possible Inclusion Manners between SC*n*As and Ditopic Guests

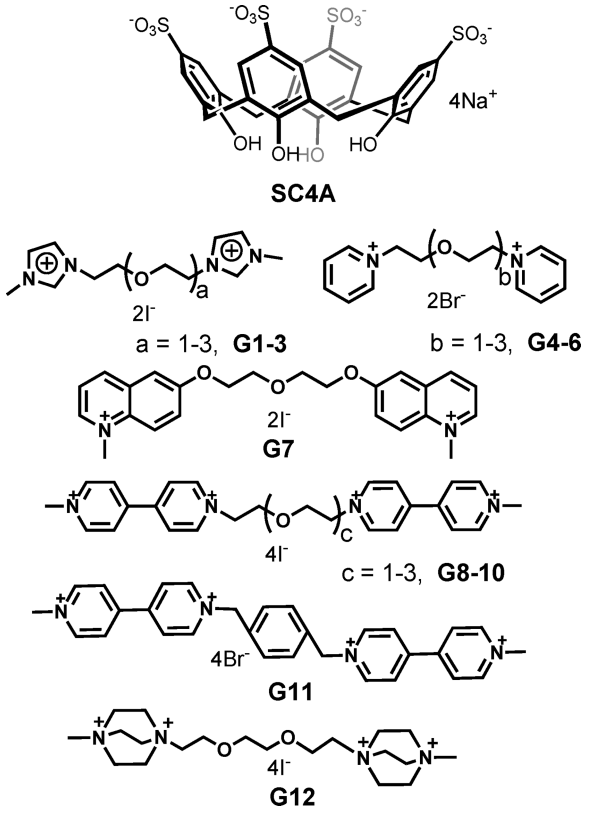


RESULTS AND DISCUSSION

Among the family of SC*n*As, the most common, SC4A, was chosen for its stable preorganized cone shape. The 12 gemini guests are divided into five species according to the different terminal groups: imidazolium (G1−G3), pyridinium (G4−G6), quinolinium (G7), viologen (G8−G11), and 1,4-diazabicyclo[2.2.2]octane (DBO, G12) of which the counterions are iodide or bromide ion (Scheme 2). These terminal groups are favored guests of SC4A with strong binding affinities

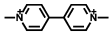
Received: December 26, 2012
Revised: January 17, 2013
Published: January 17, 2013

Scheme 2. Structural Illustration of the SC4A Host and the Positively Charged Gemini Guests G1−G12



(see Table 1 below). With these five kinds of guests in hand, we are able to analyze and discuss the influence of terminal groups

Table 1. Complex Stability Constants (K_S/M^{-1}), Enthalpy [$\Delta H°$/(kJ·mol^{-1})], and Entropy Changes [$T\Delta S°$/(kJ·mol^{-1})] for the Intermolecular Complexation of SC4A with Guests in Aqueous Solution (pH = 7.0) at 298.15 K

Guest	K_S	$\Delta H°$	$T\Delta S°$
	(2.9±0.1) × 10^5	−28.0±0.3	3.2±0.2
	(6.4±0.3) × 10^5	−31.2±0.1	1.9±0.1
	(9.3±0.1) × 10^5 [b]	−27.2±0.2[b]	6.8±0.2[b]
	(1.5±0.1) × 10^7 [a]	−22.9±0.1[a]	18.0±0.1
G4	(9.3±0.1) × 10^6 [a]	−31.7±0.1[a]	8.1±0.2

[a]Determined using 1,3-dimethylimidazolium as the competitor. [b]Data from ref 15d.

to the binding structures and stoichiometries, including size, shape and charge effects. On the other hand, G1−G3 and G4−G6 are imidazolium and pyridinium guests with flexible oligo(ethylene glycol) linkers of different lengths, and also, G8−G11 are viologen guests with flexible oligo(ethylene glycol) and rigid benzyl linkers. Consequently, how and to what extent the spacers affect the binding behaviors, including length and flexibility factors, was also addressed.

^{1}H NMR spectroscopy is a powerful tool to identify the binding geometries of SC*n*As with guests.[9g] The protons of encapsulated guests shift upfield ($\Delta\delta = \delta_{complex} - \delta_{free} < 0$) owing to the ring current effect of the aromatic nuclei of SC*n*As.[4c] The fast exchange between the free guest and the complexed species on the NMR time scale results in the signals being detected as averaged single resonances.[19] Meanwhile, the $\Delta\delta$ values are always different as a result of distinguishable locations, and thereby the $\Delta\delta$ sequence is significantly informative to deduce the binding geometries, sometimes complementally validated by two-dimensional (2D) NMR spectroscopy.[5c,6d,9g,12e]

Imidazolium-Type Gemini Guests (G1−G3). The binding structures and stoichiometries of SC4A with G1−G3 were examined by NMR titrations. There are five kinds of protons in G1 to be traced (Figure 1a). Upon addition of SC4A, all protons underwent upfield shifts, and the $\Delta\delta$ values were in the order H4 ≈ H5 > H3 ≈ H2 > H1. It indicates that G1 is immersed into the SC4A cavity with the diethylene glycol spacer being included first, that is, the type I manner (inset of Figure 1a). The protons shift more and more upon gradual addition of SC4A, and then reach a plateau. The inflection point appears at the host−guest molar ratio of 1.0 by the tangent method, showing 1:1 binding stoichiometry.

On the contrary, in the G2 and G3 cases, the protons of the terminal groups underwent larger upfield shifts than those of the oligoether spacers, and the $\Delta\delta$ sequences were H3 > H2 > H4 > H1 ≈ H5 > H6 for G2 and H3 > H2 > H4 ≈ H1 > H5 > H6 ≈ H7 for G3, respectively. This is evidence that SC4A prefers to accommodate the terminal imidazolium groups rather than the oligoether spacers. The infection points appear at 1.1 for both G2 and G3, which also proves the 1:1 binding stoichiometry. With these data in hand, three possible binding manners could be assumed: types II, III, or IV (Scheme 1). To further ascertain the exact binding geometry, the complexation of SC4A with 1,3-dimethylimidazolium (the terminal group in G1−G3) was examined as a control experiment (Figure 1d). The interaction between the 1,3-dimethylimidazolium and SC4A is of the type 1:1, with its aromatic portion encapsulated into the SC4A cavity and two N atoms fixed at the upper-rim composed of sulfonate groups (inset of Figure 1d). Simultaneously, close examination shows that the $\Delta\delta$ values of H1 and H2 in G2 and G3 are almost half of those in 1,3-dimethylimidazolium. Consequently, we deduced that the complexation of SC4A with G2 and G3 should adopt the type IV manner with one of the imidazolium groups penetrating into the cavity while the other swings randomly (insets of Figure 1b,c). The type III manner should be eliminated, as the $\Delta\delta$ values of H1 and H2 in G2 and G3 would be larger than half of those in 1,3-dimethylimidazolium since, not only did the encapsulated imidazolium suffer the ring current effect of the inner cavity, but the other one suffered the ring current effect of the outer wall of calixarene. Moreover, the type II and III manners appear less likely to be entropically unfavorable from the viewpoint of conformational freedom.

Pyridinium-type gemini guests (G4−G6). As shown in Figure 2, the $\Delta\delta$ values are in the order H1 > H2 ≈ H5 > H4 ≈ H3 for G4, H1 > H2 > H3 > H4 ≈ H5 > H6 for G5, and H1 > H2 > H3 > H4 > H5 > H6 ≈ H7 for G6, respectively. In the G4 case, the inflection point of $\Delta\delta$ appears at 1.0, and then the 1:1 binding stoichiometry was also confirmed, resembling the G1 case. The Job plot (Figure S28) is also performed for SC4A with G4, consistent with the results obtained through the tangent method that the binding stoichiometry of SC4A with G4 is 1:1. However, the binding geometries between G1 and G4 should be different by comparing the $\Delta\delta$ sequences. H1 in

dx.doi.org/10.1021/jp312744d | J. Phys. Chem. B 2013, 117, 1978−1987

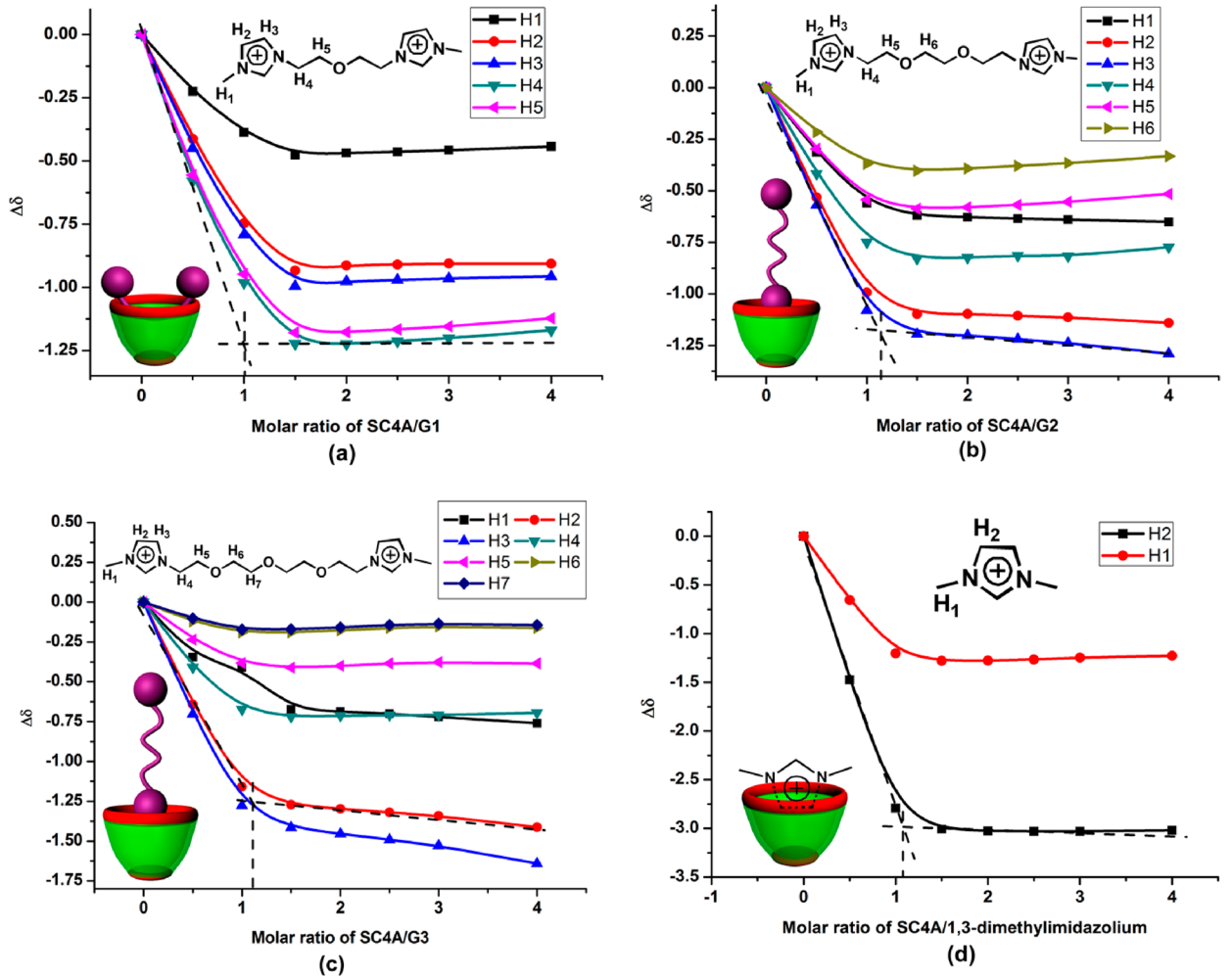


Figure 1. Plots of the $\Delta\delta$ (ppm) of the protons of (a) G1, (b) G2, (c) G3, and (d) 1,3-dimethylimidazolium versus [SC4A] in D_2O at 298.15 K (400 MHz) and [G1−G3 (1,3-dimethylimidazolium)] = 2.0 mM. Insets: inclusion manner of SC4A with G1−G3 and 1,3-dimethylimidazolium.

G4 shows the largest upfield shift, indicating that the terminal pyridinium groups should be preferentially immersed into the SC4A cavity. Moreover, it is worth noting that the spacer proton H5 also undergoes a considerable shift comparative to that of H2. Accordingly, the complexation of SC4A with G4 is inferred to adopt the type II manner with the spacer somewhat distorted (inset of Figure 2a). The different binding geometries between G1 and G4 are mainly ascribed to the charge distances between terminal groups. The positive charge of imidazolium is delocalized,[20] while that of pyridinium is fixed at the N atom. Although G1 and G4 are with the same spacer, their distances between two positive charges are different, and therefore, it is acceptable that the complexation of G1 is in type I manner, while the complexation of G4 is in type II manner.

In the G5 and G6 cases, the complexation-induced shifts of pyridinium protons are much more pronounced than those of the oligoether linkers (Figure 2b,c), which implies that SC4A mainly captures the terminal pyridinium groups into its cavity with the oligoether linkers almost outside. The binding stoichiometry is also 1:1 for both G5 and G6. From the present NMR titration results, three possible binding manners of SC4A with G5 and G6 are assumed: types II, III, or IV (Scheme 1). The $\Delta\delta$ values of H1−H3 in G5 and G6 are apparently different from those in G4, and therefore the type II manner should be reasonably eliminated in the G5 and G6 cases. To further ascertain the exact binding geometry, the binding stoichiometry and geometry of SC4A with 1-methylpyridinium (the terminal group in G4−G6) were examined as a control experiment (Figure 2d). Definitely, SC4A forms a 1:1 complex with 1-methylpyridinium, in which the aromatic portion is immersed into the cavity and the positive charged $N-CH_3$ is located at the upper-rim composed of sulfonate groups (inset of Figure 2d). Close examination shows that the $\Delta\delta$ values of H1−H3 in G5 and G6 are almost half of those in 1-methylpyridinium. We therefore deduced that the complexation of SC4A with G5 and G6 should adopt the type IV manner with one of the pyridinium groups penetrating into the cavity while the other swings randomly (insets of Figure 2b,c). Supposing the type III manner, the $\Delta\delta$ values of H1−H3 in G5 and G6 would be larger than half of those in 1-methylpyridinium since not only did the encapsulated pyridinium suffer the ring current effect of the inner cavity but also the other one suffered the ring current effect of the outer wall of calixarene. In addition, the relatively longer spacers have to be distorted if G5 and G6 were included in the type II or III manner, which is entropically unfavorable from the viewpoint of conformational freedom.

Taking an overview on G1−G6, all the complexation of SC4A gives 1:1 binding stoichiometry with different binding geometries: type I manner for G1, type II manner for G4, and

dx.doi.org/10.1021/jp312744d | J. Phys. Chem. B 2013, 117, 1978−1987

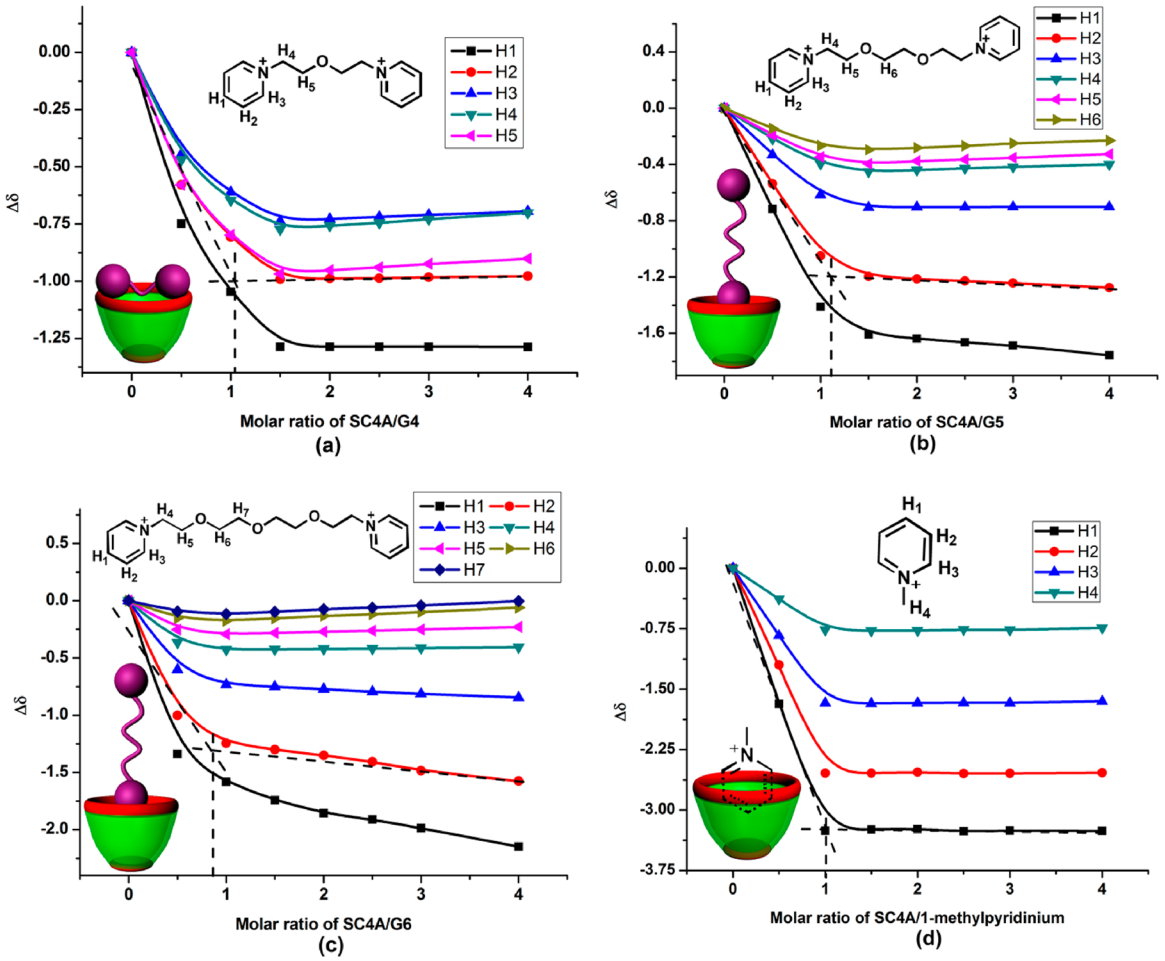
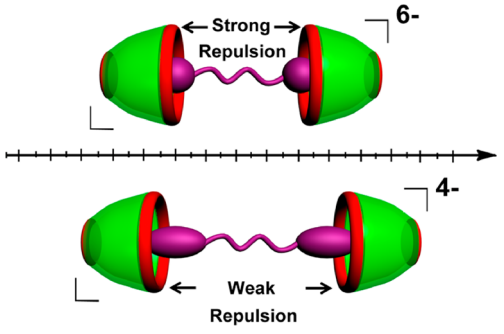


Figure 2. Plots of the $\Delta\delta$ (ppm) of the protons of (a) G4, (b) G5, (c) G6, and (d) 1-methylpyridinium versus [SC4A] in D_2O at 298.15K (400 MHz) and [G4−G6 (1-methylpyridinium)] = 2.0 mM. Insets: inclusion manner of SC4A with G4−G6 and 1-methylpyridinium.

type IV manner for G2, G3, G5, and G6. All these results are incapable of leading to supramolecular polymerization, although two identical binding sites have been grafted on one gemini guest. For G1 and G4 with short spacers, two binding sites (imidazolium or pyridinium) are concurrently held by one SC4A cavity, which is absolutely useless to join two SC4A hosts together. As a result, the spacers of ditopic guests should be designed to be long enough to span the cavities of two calixarene hosts, aiming to build supramolecular polymers.[21] For G2, G3, G5, and G6 with enough long spacers, it is somewhat strange that only one terminal group was captured by SC4A, whereas the other one remained uncomplexed. Theoretically, the ditopic guests with long spacers should adopt the type V manner upon complexation with SC4A. Why didn't they form 1:2 complexes with SC4A? One rational explanation is that the charge repulsion prevents the complexation of the second SC4A. The assumed 1:2 complexes are negatively six-charged (the ionization of phenolic hydroxyls is not considered), whereas the charge repulsion between sulfonate groups of two SC4As is very remarkable (Scheme 3). Although the binding affinities of SC4A with the terminal imidazolium and pyridinium groups are strong (up to the magnitude of 10^5 M^{-1}, see Table 1 below), the 1:2 complexation still can not occur in the present experimental condition ([Guests] = 2.0 mM) owing to the charge repulsion derived from the complexation of the second SC4A.

Scheme 3. Schematic Illustration of Charge Repulsion between Sulfonate Groups of Two SC4A in the Imidazolium (Pyridinium) and Viologen Cases



The present complexation-involved charge repulsion is concentration-dependent. Enhancing the concentrations of charge species would increase the ionic strength of the solution, which would reduce the complexation-involved charge repulsion to a greater extent since the diffusion-induced charge repulsion cannot be ignored at relatively high concentrations. So it is envisaged that G2, G3, G5, and G6 may form 1:2 complexes with SC4A at higher concentrations. To prove this hypothesis, the NMR titration experiment of the complexation of SC4A with G6 was performed at the G6 concentration of 20 mM (10 times higher than before). As expected, the 1:2

dx.doi.org/10.1021/jp312744d | J. Phys. Chem. B 2013, 117, 1978−1987

complexation was successfully achieved (Figure 3). It is therefore noticeable that the binding stoichiometry of SC4A with gemini guest is sometimes concentration-dependent.

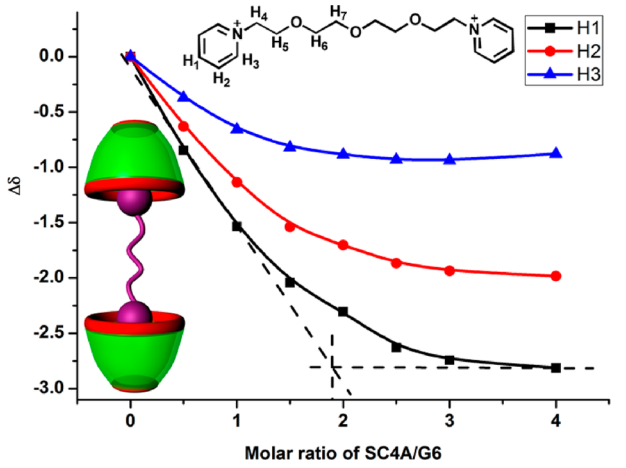


Figure 3. The plots of the $\Delta\delta$ (ppm) of the protons of G6 versus [SC4A] in D_2O at 298.15 K (400 MHz) and [G6] = 20 mM. Insets: inclusion manner of SC4A with G6.

Quinolinium-Type Gemini Guest (G7). The complexation of SC4A with G7 was investigated to identify the effect of the size of terminal groups on the host–guest binding stoichiometry. In comparison with imidazolium G2 and pyridinium G5, G7 possesses larger terminal quinolinium groups. Protons H1, H2, and H3 were selectively traced to evaluate the binding regioselectivity. Figure 4 clearly shows that

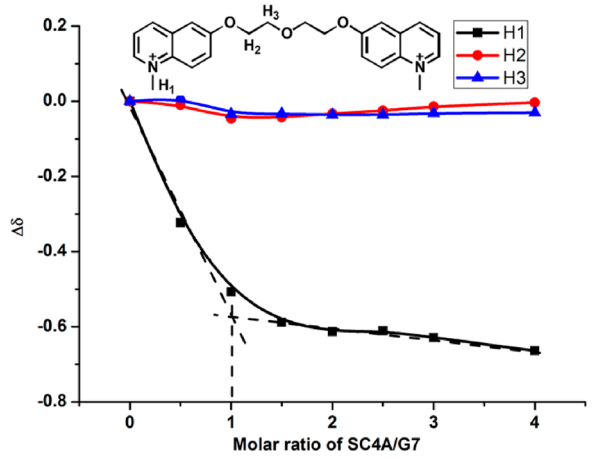


Figure 4. The plots of the $\Delta\delta$ (ppm) of the protons of G7 versus [SC4A] in D_2O at 298.15 K (400 MHz), [G7] = 2.0 mM.

the methyl proton on the quinoline ring (H1) shifts pronouncedly upon the addition of SC4A, whereas the oligoether protons suffer almost no appreciable shifts. This indicates that SC4A regioselectively accommodates the terminal quinolinium portions but not the oligoether linker. Monitoring the $\Delta\delta$ values of H1 versus the concentration of SC4A also reveals the 1:1 binding stoichiometry, which inspired us to conclude that the size of terminal groups does not solely play a crucial role in regulating the host–guest binding stoichiometry.

Viologen-Type Gemini Guests (G8–G11). We further replaced the terminal groups with viologen possessing two positive charges. Excitingly, all viologen-based guests (G8–G11) form the desired 1:2 complexes with SC4A. G8–G10 are closely comparative to G1–G3 and G4–G6 from the aspect of spacers; however, their binding behaviors with SC4A are much distinguishable. The binding geometry of G8 transforms dramatically accompanied the gradual addition of SC4A. As shown in Figure 5a, in the presence of 1 equiv or less of SC4A, the $\Delta\delta$ values of H2 and H3 are larger than that of H1, whereas in the presence of 2 equiv or more of SC4A, the $\Delta\delta$ values of H2 and H3 turn out to be smaller than that of H1. That is, 1 equiv of SC4A mainly includes the diethylene glycol spacer with the 1:1 type I manner, but 2 equiv of SC4A mainly includes the terminal viologens with 1:2 type V manner. The conversion of binding geometries is shown in Figure 5d. In the G9 and G10 cases, it is definite that SC4A prefers to accommodate the terminal viologen groups rather than the oligoether spacers, ultimately giving the 1:2 complexes.

The terminal viologen groups play the crucial role in leading to the 1:2 complexation of G8–G10, differing from the 1:1 complexation of G1–G6. In comparison with imidazolium and pyridinium, viologen possesses one more positive charge and larger molecular length. On one hand, the 1:2 complexes of G8–G10 with SC4A exhibit four negative charges, two less than those of G1–G6. On the other hand, the sulfonate groups of two SC4As in the G8–G10 complexes are more distal than those in the G1–G6 species by taking advantage of the viologen length (Scheme 3). Moreover, SC4A binds the positively dicharged viologen stronger than the monocharged imidazolium and pyridinium (see Table 1 below). All these factors contribute synergistically to the appealing 1:2 binding stoichiometry of G8–G10 with SC4A. Among these three factors, decreasing the negative charge of the complexes and increasing the host–guest binding affinity are preferably considered as two major factors, whereas elongating the distance between sulfonates is a minor factor. This is reflected from the fact that G3 and G6, with much longer spacers than G8, cannot form 1:2 complexes yet.

It is desirable that the viologen species G8–G10 are capable of forming 1:2 complexes with SC4A, which is the necessary prerequisite for building highly ordered assemblies. However, it is somewhat defective that the undesired 1:1 type I manner exists in the complexation of SC4A with G8. We wonder whether the flexibility of spacer is the troublemaker. How about the rigid spacer? G11 was therefore synthesized, where the flexible diethylene glycol spacer was replaced by the relatively rigid 1,4-dibenzyl. As shown in Figure 6a, SC4A regioselectively includes the viologen portion in G11 as expected, and G11 solely forms 1:2 complexes with SC4A, resembling the G9 and G10 cases. We determined the binding stoichiometry between SC4A and G11 by the Job method (Figure 6b), which confirmed that the host–guest ratio was 2:1, consistent with the results of the tangent method. Consequently, the flexibility of the spacer is also proven as an important factor to governing the host–guest binding stoichiometry.

DBO-Type Gemini Guest (G12). G12 possesses the same spacer as G2, G5, G7 and G9, but different terminal groups (DBO). DBO is much different from all the aforementioned terminal groups. Imidazolium, pyridinium, quinolinium, and viologen are aromatic and planar molecules, while DBO is a nonaromatic and spherical molecule. Implementing the binding behavior of SC4A with G12 is helpful to understand whether

dx.doi.org/10.1021/jp312744d | J. Phys. Chem. B 2013, 117, 1978–1987

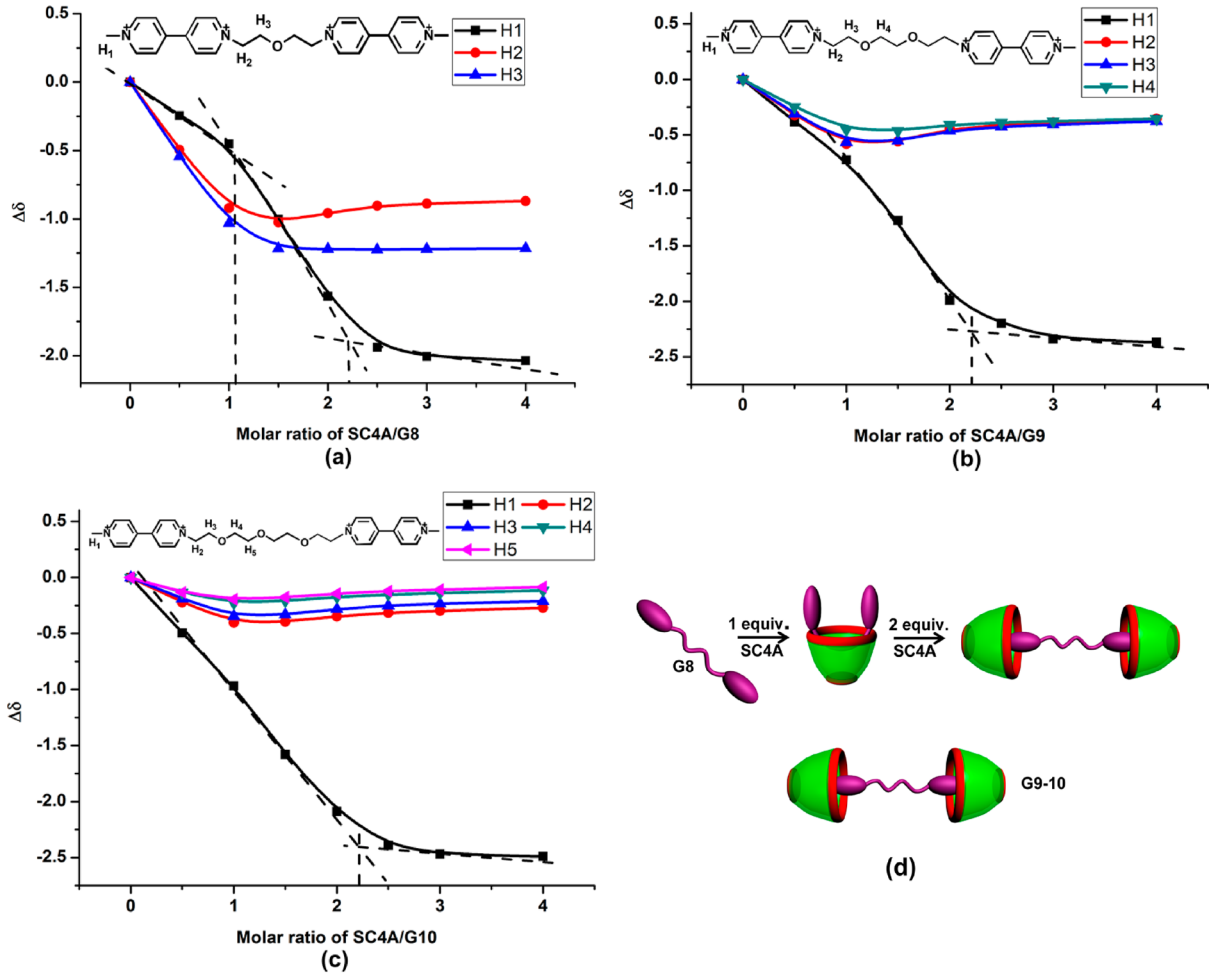


Figure 5. Plots of the $\Delta\delta$ (ppm) of the protons of (a) G8, (b) G9, (c) G10 versus [SC4A] in D_2O at 298.15 K (400 MHz) with [G8−G10] = 2.0 mM and (d) inclusion manner of SC4A with G8−G10.

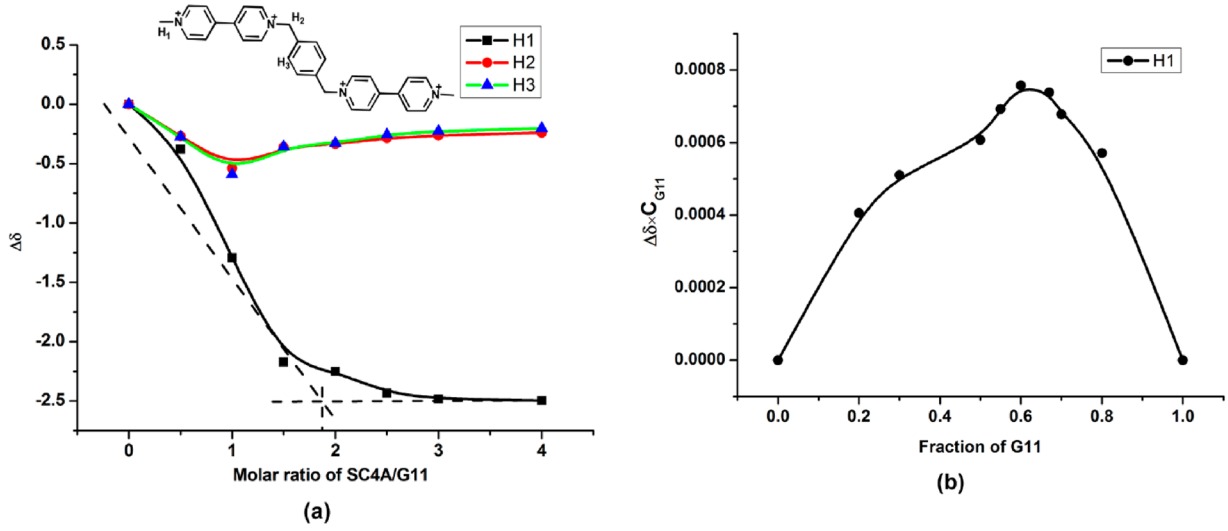


Figure 6. (a) The plots of the $\Delta\delta$ (ppm) of the protons of G11 versus [SC4A] in D_2O with [G11] = 2.0 mM at 298.15 K (400 MHz) and (b) a Job plot for G11 upon complexation with SC4A at 1 mol/L DCl (using 20% DCl, [G11] + [SC4A] = 4.0 mM, 400 MHz, 298.15 K).

the shape of the terminal group affects the binding stoichiometry. G12 is most comparative to G9 because both viologen and DBO possess two positive charges. The complexation of G12 with SC4A is almost the same as that of G9, likewise exhibiting 1:2 binding stoichiometry (Figure 7). The phenomenon of G12 reveals that the aromatic and planar terminal group is nonessential to regulate the desired binding stoichiometry. This result is reminiscent of the fact that the binding of SC4A shows spherical shape, complementarity overriding other favorable factors, such as hydrophobic and π-

dx.doi.org/10.1021/jp312744d | J. Phys. Chem. B 2013, 117, 1978−1987

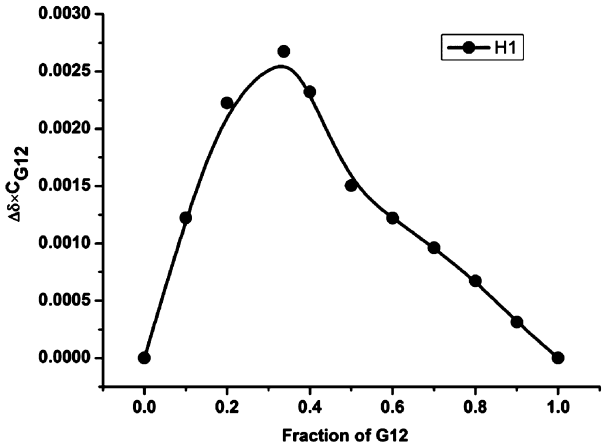


Figure 7. A Job plot for G12 upon complexation with SC4A in D_2O (400 MHz, 298.15 K, [G12] + [SC4A] = 4.0 mM).

stacking interactions offered by aromatic guests.[6d] Among all five kinds of guests, only the viologen and DBO species are apt to achieve the 1:2 type V manner, which further validates the significance of terminal charge. Essentially, SC4A always presents stronger affinities to higher charged guests.[1c,22]

Binding Affinities and Thermodynamics. The complex stability constants of SC4A with terminal subunits, imidazolium, pyridinium, viologen, and DBO, as well as G4 were measured by ITC experiments (Table 1). ITC is a powerful tool for determining the host−guest complex interactions, because it not only gives the complex stability constants (K_S), but also yields their thermodynamic parameters (enthalpy and entropy changes $\Delta H°$, $\Delta S°$). Both the stability constants and thermodynamic parameters are valuable to analyzing the binding behavior, giving quantitatively deep insight.

In all present cases, the titration data could be well fitted by computer simulation using the "one set of binding sites" model and repeated as 1:1 complex formation, so that higher-order complexes did not need to be postulated. The stability constants increase in the order of imidazolium, pyridinium, viologen, and DBO, which definitely quantifies that higher affinities are favorable for 1:2 complexes. Viologen- and DBO-based guests (G8−G12) are facile to form type V complexes with SC4A, whereas imidazolium- and pyridinium-based guests (G1−G6) are difficult. One notice should be concerned about the comparison of pyridinium/viologen pairs. The K_S value of viologen is merely 1.5 times higher than that of pyridinium; however, the binding stoichiometries are distinct between G4−G6 and G8−G10. Contrarily, the K_S value of pyridinium is 2.2 times higher than that of imidazolium, and G1−G6 retain the same binding stoichiometry. This reflects that the charge repulsion is an important factor indeed. The charge repulsion between sulfonates of two SC4As is similar in the monocharged imidazolium and pyridinium cases, which is appreciably larger than that in the dicharged viologen cases.

DBO shows the highest K_S value up to 10^7 M^{-1} with more favorable entropy, but less favorable enthalpy terms than the other guests. Two factors contribute to the favorable entropy change. On one hand, DBO is spherical, while the imidazolium, pyridinium, and viologen guests are planar. The conical cavity of SC4A shows clearly spherical shape complementarity, and then the loss of conformational freedom during the course of the complexation of SC4A with DBO is not as large as those in the other planar cases. On the other hand, the desolvation effect between DBO and sulfonate groups is more extensive that of the other guests. It can be seen that discharged viologen gives much more favorable entropy change than monocharged imidazolium and pyridinium. The complexation-derived desolvation is charge-involved: the higher the charges, the more extensive the desolvation effect.[3a,4b] The two positive charges of DBO are more proximate than those of viologen, which is more appropriate to participate in the complexation-derived desolvation. For the less favorable enthalpy term, DBO is nonaromatic, and thereby, the $\pi\cdots\pi$ interactions between SC4A and aromatic guests are reasonably knocked off.

The titration data of SC4A with G4 could be well fitted by computer simulation using the "one set of binding sites" model, showing a good "*N*" value of 0.9 in the curve fitting. The experimental "*N*" value agrees well with the aforementioned 1:1 binding stoichiometry by NMR titration. G4 presents 15 times higher K_S values than its subunit, pyridinium. The enthalpy change of G4 is comparative to that of pyridinium, whereas its entropy change is much more favorable than that of pyridinium, and even some larger than that of viologen. The entropy term of G4 coincides with the type II manner in that two positive charges in G4 are concurrently involved in the desolvation effect. The stronger 1:1 complexation of SC4A with G4 prevents the desired 1:2 type V manner. Such phenomenon was also observed in the G1 and G8 cases to a different extent.

CONCLUSIONS

In summary, the inclusion complexation of SC4A with a series of gemini guests has been demonstrated by NMR as well as ITC measurements. The binding stoichiometry and geometry depend on the spacer length, flexibility, terminal charge, and also concentration, but not terminal size and shape. Guests with highly charged terminal groups and long rigid spacers are appealed for 1:2 stoichiometry, which is in nature governed by three key factors: binding manner, affinity, and charge repulsion. A total of five manners were assumed at the beginning (Scheme 1), and four of them were observed in the present work. Types I and II are useless to fulfill 1:2 complexation. Type IV is a potential precursor for 1:2 complexation, which can evolve into the desired type V upon enhancing concentration. The charge repulsion between sulfonate groups of two SC4As is the dominant negative force to prevent 1:2 complexation. Increasing guest charge and elongating spacer length are two effective approaches to neutralize the charge repulsion. More importantly, enhancing binding affinity is an essential innovation. Strong affinity not only overcomes the disfavored charge repulsion, but is also always demanded to build truly polymeric materials. In principle, our present results are significantly valuable and helpful to design water-soluble calixarene-based supramolecular assemblies. However, one should notice that the binding behavior of SC*n*A derivatives modified at the lower rim sometimes differs from that of mother SC*n*As.[9e,15d] For supramolecular assembly, lower-rim bridged bis-SC*n*As are generally required.

EXPERIMENTAL SECTION

Materials. The host molecule, *p*-sulfonatocalix[4]arene (SC4A)[23] was synthesized and purified referring to the literature process. The guests G1−G12[24] were synthesized and purified according to the respective literature procedures. For a general procedure, the precursor of the terminal group

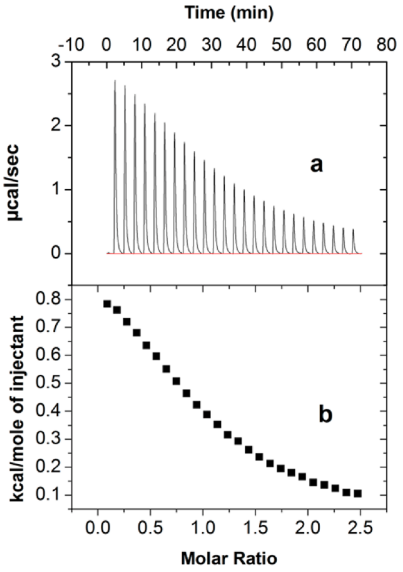


Figure 8. Competition ITC experiments on complexation of DBO with SC4A in the solution of 1,3-dimethylimidazolium used as competitor (pH = 7.0) at 298.15 K. (a) Raw ITC data for sequential 25 injections (10 μL per injection) of DBO solution (10.42 mM) injecting into 19.88 mM 1,3-dimethylimidazolium with 0.81 mM SC4A solution. (b) Apparent reaction heat obtained from the integration of calorimetric traces.

(imidazolium, pyridinium, quinolinium, viologen and DBO; about 4 mmol) was dissolved in anhydrous CH_3CN (10 mL) and was heated to reflux in a 50 mL three-neck round-bottom flask under nitrogen atmosphere. Then oligoether glycol diiodide/dibromide (1 mmol) in anhydrous CH_3CN (10 mL) was dropped into the flask with stirring, and the reaction mixture was maintained under reflux for an additional 24 h. Upon cooling the mixture down to room temperature, it was dropped into the Et_2O (250 mL), and the precipitate formed immediately. After cooling to 0 °C for several hours, the precipitate produced was filtered and recrystallized from anhydrous CH_3CN to afford the product as a solid, and then dried under vacuum (yields: 40−65%). This product (0.4 mmol) was dissolved in dimethylformamide (DMF; 10 mL) then the CH_3I (2 mmol) was added. The reaction mixture was stirred at 90 °C for 24 h. The solids were collected and washed with anhydrous CH_3CN. It should be mentioned that the precipitate G11 with iodide and bromide ion as counterions was exchanged by PF_6^- and then Br^-. The product was dried under vacuum overnight (yields: 60−85%). All these products were identified via ^1H NMR spectroscopy in D_2O (Figures S1−12). We tried our best to obtain the complexes of SC4A with G1−G12 in their monocrystalline, but unfortunately we did not get it. Maybe it is because of the flexibility of the oligoether glycol bridge chain.

All other chemicals were commercially available, were of reagent grade, and were used without further purification. pH 7.0 solutions were prepared with distilled, deionized water, adjusted with 1.0 M sodium hydroxide (NaOH), and verified on a pH meter calibrated with two standard buffer solutions.

Measurements. *NMR Spectroscopy.* ^1H NMR spectra were recorded on a Bruker AV400 spectrometer in D_2O at 298.15 K, using 2,2-dimethyl-2-silapentane-5-sulfonate as an internal reference. The guest concentration was kept constant, while the host concentration was varied. All the SC4A and guests were mixed in the molar ratios of about 0.5−4:1, with the concentrations of guest at 2.0 mM. Solutions for ^1H NMR titrations were prepared by mixing 250 μL of 4.0 mM guests with appropriate quantities of 16.0 mM SC4A in the NMR tubes and then diluted with D_2O to 500 μL.

Solutions for Job's plots were prepared by mixing the 4.0 mM solution of guests with the 4.0 mM solution of SC4A so that the sum of their concentrations was kept constant, but their molecular fraction varied from 1:9 to 9:1. In addition, the solubility of host−guest complexes between G11 with SC4A is not as good as that of G1−G10 with SC4A in neutral solution;

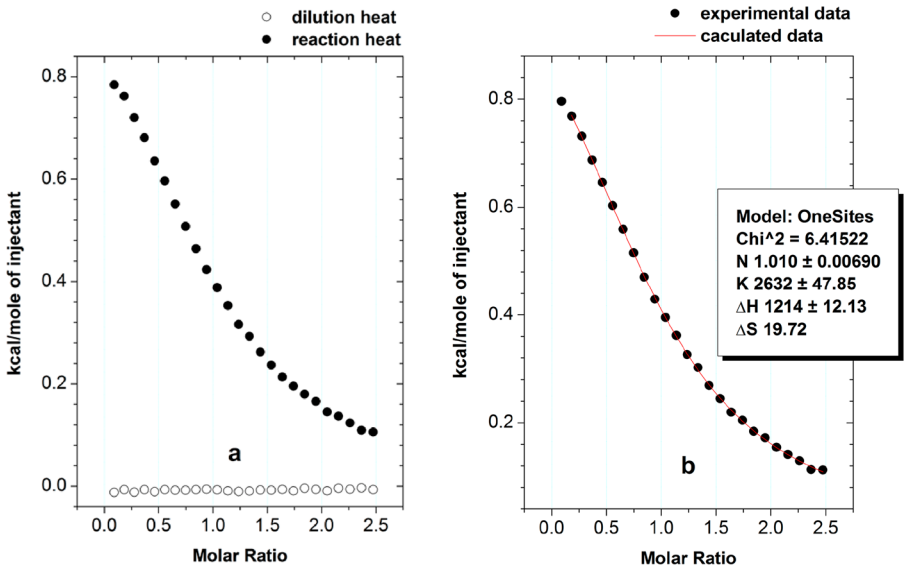


Figure 9. (a) Heat effects of the dilution and of the complexation reaction of DBO with SC4A in the solution of 1,3-dimethylimidazolium used as a competitor for each injection during the titration microcalorimetric experiment at pH = 7.0. (b) "Net" heat effects of complexation of DBO with SC4A in the solution of 1,3-dimethylimidazolium used as a competitor for each injection, obtained by subtracting the dilution heat from the reaction heat, which was fitted by computer simulation using the "one set of binding sites" model.

dx.doi.org/10.1021/jp312744d | J. Phys. Chem. B 2013, 117, 1978−1987

therefore the Job's plot for the G11 complex with SC4A was measured at 1 mol/L DCl (using 20% DCl).

Isothermal Titration Calorimetry. A thermostatted and fully computer-operated isothermal calorimetry (VP-ITC) instrument, purchased from Microcal Inc., Northampton, MA, was used for all microcalorimetric experiments. The VP-ITC instrument was calibrated chemically by measurement of the complexation reaction of β-cyclodextrin with cyclohexanol, and the obtained thermodynamic data were in good agreement (error <2%) with the literature data,[25] as well as by measurement of the complexation reaction of SC4A with methyl viologen, and the obtained thermodynamic data were in good agreement (error <5%) with the literature data.[5e] All microcalorimetric titrations were performed in aqueous solution (pH = 7.0) at atmospheric pressure and 298.15 K. Each solution was degassed and thermostatted by a ThermoVac accessory before the titration experiment. Twenty-five successive injections were made for each titration experiment. A constant volume (10 μL per injection) of guests (3.50−22.57 mM) solution in a 0.250 mL syringe was injected into the reaction cell (1.4227 mL) charged with host molecule solution (0.20−1.54 mM) in the same aqueous solution (Figures S32−S37). The heat of dilution was measured by injecting the guest solution into a blank solution containing no host, and the net heat effect was obtained by subtracting this value from the overall heat effect observed; their average values with associated errors are listed in Table 1. Because the association constants of the complexation between SC4A with DBO or G4 are extremely large, the ITC experiments were performed by using the multistep competition method with 1,3-dimethylimidazolium as a competitor. A representative titration curve was shown in Figures 8 and 9. The data were analyzed and fitted by the Origin program (MicroCal). And then the complex stability constant (K_S) and molar reaction enthalpy (ΔH°) enabled calculation according to

$$K_S = [\text{competitor}] \times K_{exp} \times K_{competitor}$$

$$\Delta H = \Delta H^\circ_{competitor} + \Delta H^\circ_{exp}$$

■ ASSOCIATED CONTENT

Supporting Information

Characterization data for compounds G1−G12, chemical shift changes upon the complexation, Job's plots, thermodynamic parameters, as well as calorimetric titration curves. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: yuliu@nankai.edu.cn.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was supported by the 973 Program (2011CB932502), and the NSFC (20932004, 21172119, 91227107), which are gratefully acknowledged.

■ REFERENCES

(1) (a) Shinkai, S.; Mori, S.; Tsubaki, T.; Sone, T.; Manabe, O. *Tetrahedron Lett.* **1984**, *25*, 5315−5318. (b) Sánchez, A.; Jiménez, R.; Ternero, F.; Mesa, R.; Piñero, C. A.; Muriel, F.; Lopez-Cornejo, P. *J. Phys. Chem. B* **2007**, *111*, 10697−10702. (c) Guo, D.-S.; Wang, K.; Liu, Y. *J. Inclusion Phenom. Macrocyclic Chem.* **2008**, *62*, 1−21.

(2) (a) Mustafina, A. R.; Skripacheva, V. V.; Kazakova, E. K.; Markarova, N. A.; Kataev, V. E.; Ermolaevay, L. V. *J. Inclusion Phenom. Macrocyclic Chem.* **2002**, *42*, 77−81. (b) Buschmann, H.-J.; Mutihac, L.; Schollmeyer, E. *J. Inclusion Phenom. Macrocyclic Chem.* **2003**, *46*, 133−137. (c) de Assis, V.; Teixeira, M. G.; Soares, C. G. P.; Lopes, J. F.; Carvalho, G. S. L.; Lourenço, M. C. S.; de Almeida, M. V.; de Almeida, W. B.; Fernandes, S. A. *Eur. J. Pharm. Sci.* **2012**, *47*, 539−548.

(3) (a) Bonal, C.; Israëli, Y.; Morel, J.-P.; Morel-Desrosiers, N. *J. Chem. Soc., Perkin Trans. 2* **2001**, 1075−1078. (b) Morel, J.-P.; Morel-Desrosiers, N. *Org. Biomol. Chem.* **2006**, *4*, 462−465. (c) Cuc, D.; Bouguet-Bonnet, S.; Morel-Desrosiers, N.; Morel, J.-P.; Nutzenhardt, P.; Canet, D. *J. Phys. Chem. B* **2009**, *113*, 10800−10807. (d) Basilio, N.; García-Río, L.; Martín-Paster, M. *J. Phys. Chem. B* **2010**, *114*, 7201−7206.

(4) (a) Shinkai, S.; Araki, K.; Matsuda, T.; Nishiyama, N.; Ikeda, H.; Takasu, I.; Iwamoto, M. *J. Am. Chem. Soc.* **1990**, *112*, 9053−9058. (b) StöDeman, M.; Dhar, N. *J. Chem. Soc., Faraday. Trans.* **1998**, *94*, 899−903. (c) Arena, G.; Casnati, A.; Contino, A.; Lombardo, G. G.; Sciotto, D.; Ungaro, R. *Chem.−Eur. J.* **1999**, *5*, 738−744. (d) Arena, G.; Gentile, S.; Gulino, F. G.; Sciotto, D.; Sgarlata, C. *Tetrahedron Lett.* **2004**, *45*, 7091−7094. (e) Ghoufi, A.; Bonal, C.; Morel, J. P.; Morel-Desrosiers, N.; Malfreyt, P. *J. Phys. Chem. B* **2004**, *108*, 5095−5104. (f) Liu, Y.; Yang, E.-C.; Chen, Y. *Thermochim. Acta* **2005**, *429*, 163−166.

(5) (a) Liu, Y.; Guo, D.-S.; Yang, E.-C.; Zhang, H.-Y.; Zhao, Y.-L. *Eur. J. Org. Chem.* **2005**, 162−170. (b) Liu, Y.; Yang, E.-C.; Chen, Y.; Guo, D.-S.; Ding, F. *Eur. J. Org. Chem.* **2005**, 4581−4588. (c) Liu, Y.; Guo, D.-S.; Zhang, H.-Y.; Ma, Y.-H.; Yang, E.-C. *J. Phys. Chem. B* **2006**, *110*, 3428−3434. (d) Liu, Y.; Ma, Y.-H.; Chen, Y.; Guo, D.-S.; Li, Q. *J. Org. Chem.* **2006**, *71*, 6468−6473. (e) Guo, D.-S.; Wang, L.-H.; Liu, Y. *J. Org. Chem.* **2007**, *72*, 7775−7778. (f) Gaeta, C.; Caruso, T.; Mincolelli, M.; Troisi, F.; Vasca, E.; Neri, P. *Tetrahedron* **2008**, *64*, 5370−5378.

(6) (a) Arena, G.; Contino, A.; F. Gulino, G.; Magrì, A.; Sciotto, D.; Ungaro, R. *Tetrahedron Lett.* **2000**, *41*, 9327−9330. (b) Kon, N.; Iki, N.; Miyano, S. *Org. Biomol. Chem.* **2003**, *1*, 751−755. (c) Ghoufi, A.; Morel, J. P.; Morel-Desrosiers, N.; Malfreyt, P. *J. Phys. Chem. B* **2005**, *109*, 23579−23587. (d) Bakirci, H.; Koner, A. L.; Nau, W. M. *J. Org. Chem.* **2005**, *70*, 9960−9966.

(7) (a) Costanzo, L. D.; Geremia, S.; Randaccio, L.; Purrello, R.; Lauceri, R.; Sciotto, D.; Gulino, F. G.; Pavone, V. *Angew. Chem., Int. Ed.* **2001**, *40*, 4245−4247. (b) Sueishi, Y.; Inazumi, N.; Hanaya, T. *J. Phys. Org. Chem.* **2005**, *18*, 448−455. (c) Lau, V.; Heyne, B. *Chem. Commun.* **2010**, *46*, 3595−3597.

(8) (a) Douteau-Guével, N.; Coleman, A. W.; Morel, J.-P.; Morel-Desrosiers, N. *J. Chem. Soc., Perkin Trans. 2* **1999**, 629−633. (b) Douteau-Guével, N.; Perret, F.; Coleman, A. W.; Morel, J.-P.; Morel-Desrosiers, N. *J. Chem. Soc., Perkin Trans. 2* **2002**, 524−532. (c) Arena, G.; Casnati, A.; Contino, A.; Magrì, A.; Sansone, F.; Sciotto, D.; Ungaro, R. *Org. Biomol. Chem.* **2006**, *4*, 243−249. (d) Megyesi, M.; Biczók, L. *J. Phys. Chem. B* **2010**, *114*, 2814−2819.

(9) (a) Shinkai, S.; Araki, K.; Matsuda, T.; Manabe, O. *Bull. Chem. Soc. Jpn.* **1989**, *62*, 3856−3862. (b) Koh, K. N.; Araki, K.; Ikeda, A.; Otsuka, H.; Shinkai, S. *J. Am. Chem. Soc.* **1996**, *118*, 755−758. (c) Arena, G.; Casnati, A.; Contino, A.; Gulino, F. G.; Sciotto, D.; Ungaro, R. *J. Chem. Soc., Perkin Trans. 2* **2000**, 419−423. (d) Mendes, A.; Bonal, C.; Morel-Desrosiers, N.; Morel, J.-P.; Malfreyt, P. *J. Phys. Chem. B* **2002**, *106*, 4516−4524. (e) Bakirci, H.; Nau, W. M. *Adv. Funct. Mater.* **2006**, *16*, 237−242. (f) Souchon, V.; Leray, I.; Valeur, B. *Chem. Commun.* **2006**, 4224−4226. (g) Xiong, D.; Chen, M.; Li, H. *Chem. Commun.* **2008**, 880−882. (h) Cui, J.; Uzunova, V. D.; Guo, D.-S.; Wang, K.; Nau, W. M.; Liu, Y. *Eur. J. Org. Chem.* **2010**, 1704−1710. (i) Li, Q.; Guo, D.-S.; Qian, H.; Liu, Y. *Eur. J. Org. Chem.* **2012**, 3962−3971. (j) Guo, D.-S.; Zhang, H.-Q.; Ding, F.; Liu, Y. *Org. Biomol. Chem.* **2012**, *10*, 1527−1536.

(10) (a) Orr, G. W.; Barbour, L. J.; Atwood, J. L. *Science* **1999**, *285*, 1049−1052. (b) Atwood, J. L.; Barbour, L. J.; Dalgarno, S. J.; Hardie, M. J.; Raston, C. L.; Webb, H. R. *J. Am. Chem. Soc.* **2004**, *126*, 13170−13171. (c) Atwood, J. L.; Barbour, L. J.; Hardie, M. J.; Raston, C. L. *Coord. Chem. Rev.* **2001**, *222*, 3−32. (d) Dalgarno, S. J.; Atwood, J. L.; Raston, C. L. *Chem. Commun.* **2006**, 4567−4574. (e) Danylyuk, O.; Suwinska, K. *Chem. Commun.* **2009**, 5799−5813. (f) Ling, I.; Alias, Y.; Raston, C. L. *New J. Chem.* **2010**, *34*, 1802−1811.

(11) (a) Shinkai, S.; Mori, S.; Koreishi, H.; Tsubaki, T.; Manabe, O. *J. Am. Chem. Soc.* **1986**, *108*, 2409−2416. (b) Goto, K.; Murakami, Y.; Ueoka, R. *J. Mol. Catal. B: Enzym.* **2001**, *18*, 985−989. (c) Goto, K.; Yano, Y.; Okada, E.; Liu, C.-W.; Yamamoto, K.; Ueoka, R. *J. Org. Chem.* **2003**, *68*, 865−870. (d) Kaliappan, R.; Kaanumalle, L. S.; Natarajan, A.; Ramamurthy, V. *Photochem. Photobiol. Sci.* **2006**, *5*, 925−930. (e) Liu, Y.-L.; Liu, L.; Wang, Y.-L.; Han, Y.-C.; Wang, D.; Chen, Y.-J. *Green Chem.* **2008**, *10*, 635−640. (f) Ryzhkina, I. S.; Kiseleva, Y. V.; Solovéva, S. E.; Pilishkina, L. M.; Valitova, Y. N.; Konovalov, A. I. *Russ. Chem. Bull., Int. Ed.* **2009**, *58*, 2506−2511. (g) Ryzhkina, I. S.; Kiseleva, Y. V.; Murtazina, L. I.; Valitova, Y. N.; Solovéva, S. E.; Pilishkina, L. M.; Konovalov, A. I. *Russ. Chem. Bull., Int. Ed.* **2010**, *59*, 1327−1335.

(12) (a) Houmadi, S.; Coquière, D.; Legrand, L.; Fauré, M. C.; Goldmann, M.; Reinaud, O.; Rémita, S. *Langmuir* **2007**, *23*, 4849−4855. (b) Basilio, N.; García-Río, L. *Chem.−Eur. J.* **2009**, *15*, 9315−9319. (c) Francisco, V.; Basilio, N.; García-Río, L.; Leis, J. R.; Maques, E. F.; Vázquez-Vázquez, C. *Chem. Commun.* **2010**, *46*, 6551−6553. (d) Wang, K.; Guo, D.-S.; Liu, Y. *Chem.−Eur. J.* **2010**, *16*, 8006−8011. (e) Basílio, N.; Garcia-Rio, L.; Martín-Pastor, M. *Langmuir* **2012**, *28*, 2404−2414. (f) Wang, K.; Guo, D.-S.; Liu, Y. *Chem.−Eur. J.* **2012**, *18*, 8758−8764.

(13) (a) Bakirci, H.; Koner, A. L.; Dickman, M. H.; Kortz, U.; Nau, W. M. *Angew. Chem., Int. Ed.* **2006**, *45*, 7400−7404. (b) Bakirci, H.; Koner, A. L.; Schwarzlose, T.; Nau, W. M. *Chem.−Eur. J.* **2006**, *12*, 4799−4807. (c) Hennig, A.; Bakirci, H.; Nau, W. M. *Nat. Methods* **2007**, *4*, 629−632. (d) Nau, W. M.; Ghale, G.; Hennig, A.; Bakirci, H.; Bailey, D. M. *J. Am. Chem. Soc.* **2009**, *131*, 11558−11570. (e) Florea, M.; Nau, W. M. *Org. Biomol. Chem.* **2010**, *8*, 1033−1039. (f) Guo, D.-S.; Uzunova, V. D.; Su, X.; Nau, W. M.; Liu, Y. *Chem. Sci.* **2011**, *2*, 1722−1734.

(14) (a) Perret, F.; Lazar, A. N.; Coleman, A. W. *Chem. Commun.* **2006**, 2425−2438. (b) Wang, K.; Guo, D.-S.; Zhang, H.-Q.; Li, D.; Zheng, X.-L.; Liu, Y. *J. Med. Chem.* **2009**, *52*, 6402−6412. (c) Wang, K.; Guo, D.-S.; Wang, X.; Liu, Y. *ACS. Nano* **2011**, *5*, 2880−2894. (d) Perret, F.; Coleman, A. W. *Chem. Commun.* **2011**, *47*, 7303−7319. (e) Wang, G.-F.; Ren, X.-L.; Zhao, M.; Qiu, X.-L.; Qi, A.-D. *J. Agric. Food Chem.* **2011**, *59*, 4294−4299. (f) Guo, D.-S.; Wang, K.; Wang, Y.-X.; Liu, Y. *J. Am. Chem. Soc.* **2012**, *134*, 10244−10250.

(15) (a) Guo, D.-S.; Chen, K.; Zhang, H.-Q.; Liu, Y. *Chem. Asian J.* **2009**, *4*, 436−445. (b) Guo, D.-S.; Chen, S.; Qian, H.; Zhang, H.-Q.; Liu, Y. *Chem. Commun.* **2010**, *46*, 2620−2622. (c) Ma, X.; Sun, R.; Li, W.; Tian, H. *Polym. Chem.* **2011**, *2*, 1068−1070. (d) Qian, H.; Guo, D.-S.; Liu, Y. *Chem.−Eur. J.* **2012**, *18*, 5087−5095. (e) Qian, H.; Guo, D.-S.; Liu, Y. *Asian J. Org. Chem.* **2012**, *1*, 155−159.

(16) StöDeman, M.; Dhar, N. *Thermochim. Acta* **1998**, *320*, 33−38.

(17) Wu, S.; Wang, G.; Zou, L.; Wang, Q.; Ma, X. *Dyes Pigm.* **2012**, *95*, 436−442.

(18) (a) Guo, D.-S.; Zhang, H.-Y.; Li, C.-J.; Liu, Y. *Chem. Commun.* **2006**, 2592−2594. (b) Makha, M.; Alias, Y.; Raston, C. L.; Sobolev, A. N. *New J. Chem.* **2008**, *32*, 83−88. (c) Guo, D.-S.; Su, X.; Liu, Y. *Cryst. Growth Des.* **2008**, *8*, 3514−3517. (d) Ling, I.; Alias, Y.; Sobolev, A. N.; Raston, C. L. *Cryst. Growth Des.* **2009**, *9*, 4497−4503. (e) Su, X.; Guo, D.-S.; Liu, Y. *CrystEngComm* **2010**, *12*, 947−952. (f) Ling, I.; Alias, Y.; Sobolev, A. N.; Raston, C. L. *CrystEngComm* **2010**, *12*, 1869−1875. (g) Ling, I.; Alias, Y.; Sobolev, A. N.; Byrne, L. T.; Raston, C. L. *CrystEngComm* **2011**, *13*, 787−793. (h) Ling, I.; Alias, Y.; Rahim, M. S. A.; Skelton, B. W.; Byrne, L. T.; Raston, C. L. *Aust. J. Chem.* **2012**, *65*, 755−762 The binding behaviors in solution are always different from that in the solid state. In several examples, 1:2 stoichiometry was observed in the solid state, whereas just 1:1 stoichiometry was seen in solution. 1:1 solution complexes act generally as precursors to 1:2 solid-state complexes.

(19) Bonaccorso, C.; Sgarlata, C.; Grasso, G.; Zito, V.; Sciotto, D.; Arena, G. *Chem. Commun.* **2011**, *47*, 6117−6119.

(20) Hunt, P. A.; Kirchner, B.; Welton, T. *Chem.−Eur. J.* **2006**, *12*, 6762−6775.

(21) (a) Gattuso, G.; Notti, A.; Pappalardo, A.; Parisi, M. F.; Pisagatti, I.; Pappalardo, S.; Garozzo, D.; Messina, A.; Cohen, Y.; Slovak, S. *J. Org. Chem.* **2008**, *73*, 7280−7289. (b) Guo, D.-S.; Liu, Y. *Chem. Soc. Rev.* **2012**, *41*, 5907−5921.

(22) (a) Böhmer, V. *Angew. Chem., Int. Ed.* **1995**, *34*, 713−745. (b) Pochini, A.; Ungaro, R. Calixarenes and Related Hosts. In *Comprehensive Supramolecular. Chemistry*; Vögtle, F., Ed.; Pergamon: Oxford, 1996; Vol. *2*, pp 103−149. (c) Ikeda, A.; Shinkai, S. *Chem. Rev.* **1997**, *97*, 1713−1734. (d) For a book about calixarenes, see Gutsche, C. D. *Calixarenes Revisited*; Stoddart, J. F., Ed.; Monographs in Supramolecular Chemistry; J. F. Royal Society of Chemistry: Cambridge, UK, 1998.

(23) Arena, G.; Contino, A.; Lombardo, G. G.; Sciotto, D. *Thermochim. Acta* **1995**, *264*, 1−11.

(24) (a) Bourlier, J.; Jouaiti, A.; Kyritsakas-Gruber, N.; Allouche, L.; Planeix, J.-M.; Hosseini, M. W. *Chem. Commun.* **2008**, 6191−6193. (b) Bara, J. E.; Hatakeyama, E. S.; Gabriel, C. J.; Zeng, X.; Lessmann, S.; Gin, D. L.; Noble, R. D. *J. Membr. Sci.* **2008**, *316*, 186−191. (c) Zeng, Z.; Phillips, B. S.; Xiao, J.-C.; Shreeve, J. M. *Chem. Mater.* **2008**, *20*, 2719−2726. (d) Engel, R.; Rizzo, J. I.; Rivera, C.; Ramirez, M.; Huang, M. L.; Montenegro, D.; Copodiferro, C.; Behaj, V.; Thomas, M.; Klaritch-vrana, B.; Engel, J. F. *Chem. Phys. Lipids* **2009**, *158*, 61−69. (e) Deroo, S.; Rauwald, U.; Robinson, C. V.; Scherman, O. A. *Chem. Commun.* **2009**, 644−646. (f) Musilek, K.; Komloova, M.; Zavadova, V.; Hrabinova, M.; Pohanka, M.; Dohnal, V.; Nachon, Dolezal, F.; M.; Kuca, K.; Jung, Y.-S. *Bioorg. Med. Chem. Lett.* **2010**, *20*, 1763−1766.

(25) Rekharsky, M. V.; Inoue, Y. *Chem. Rev.* **1998**, *98*, 1875−1917.