Synthesis of 9,10-Bis-ketoenaminoanthryl and 9,10-Bis-isoxazolylanthryl Linked Biscalix[4]arenes: Atropisomers and Molecular Recognitions

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S *Supporting Information*

ABSTRACT: An efficient synthetic pathway for the synthesis of biscalix[4]arenes **5−10** using 1,3-dipolar cycloaddition reactions is reported. Biscalix[4]arene **10** is capable of forming a complex with methyl viologen because of favorable cation−π interactions and a proper cavity size to accommodate the guest. Moreover, biscalix[4]arenes **8a** and **8b** were found to be atropisomers at room temperature. These two conformers were unable to exchange at room temperature because of the restricted rotation of the C_9-C_{11} or $C_{10}-C_{12}$ bonds of the β-amino-α,β-unsaturated ketones of anthracene.
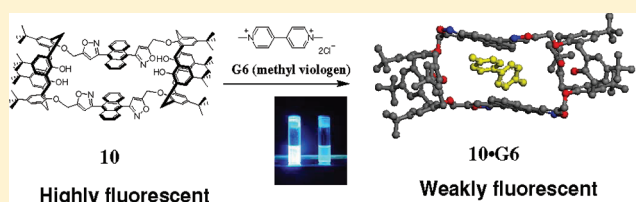
INTRODUCTION

Biscalixarenes[1] have been studied extensively in recent years because the structures usually contain interesting properties including allosteric effect,[2] intramolecular oscillation,[3] and conformational conversion.[4] An internal cavity, formed naturally through the linkage of two calixarenes, can be used as a host not only for metal ions but also for neutral molecules. For example, Gutsche and co-workers reported that 5,5′-biscalix[5]arene can be used to selectively recognize full-erene[70] over fullerene[60], where the biscalix[5]arene undergoes an anti to syn conformational change upon complexation with a fullerene to maximize the interaction between host and guest.[4a]

Methyl viologen is one of the most widely used herbicides in the world. It is shown to be toxic to humans and animals and is linked to the development of Parkinson's disease;[5] accordingly, it is highly desirable to have a selective and sensitive method in the fast screening of methyl viologen. Currently, most of the detection of methyl viologen relies on ^{1}H NMR titration experiments using various macrocycles such as calix[4]arenes,[6] crown ethers,[7] triptycenes,[8] and pillar[5]arenes.[9] There has been very few reports on the fluorescent sensing of methyl viologen. To the best of our knowledge, Wagner and Isaacs were the first to report a fluorescent sensing of methyl viologen using cucurbit[6]uril as the host.[10] The design and synthesis of a highly specific fluorescent sensor for viologen is still demanding, and it would have following benefits: high sensitivity, easy to use, low cost, and low background interference.

We have been using a strategy to construct a variety of functionalized isoxazoline and isoxazole unit(s) onto the calix[4]arene skeletons through double and/or quadruple 1,3-dipolar cycloaddition reactions of alkenes/alkynes with aryl nitrile oxides.[11,12] In order to further expand the diversity of biscalix[4]arenes, we also explored possible ring-opening reactions of mono- and bis-isoxazole substituted calix[4]-arenes.[12−14] To our delight, $Mo(CO)_6$-mediated ring-opening reactions of these isoxazole-substituted calix[4]arenes led to the formation of various enaminone (β-amino-α,β-unsaturated ketone) appended calix[4]arenes efficiently.[14] Using the protocol described above, we report herein the synthesis of biscalix[4]arenes **6−10**, which contain an ellipsoidal cavity and/or an anthryl group as fluorophore. The ring-opening reaction of biscalixarene **7** led to two 9,10-bis-ketoenaminoanthryl biscalix[4]arenes, **8a** and **8b**, which showed interesting atropisomeric properties.[15] The application of biscalix[4]arene **10** as a fluorescent chemosensor for methyl viologen is also studied.

RESULTS AND DISCUSSION

The synthetic pathways for biscalix[4]arenes **5**, **7**, and **10** are depicted in Scheme 1. Our synthetic strategy for linking two calix[4]arenes started with the double 1,3-dipolar cycloaddition reactions between aryl dinitrile oxides (prepared in situ from **3** and **4**) and propargyl ether to yield **5** and **7** in 43% and 62% yield, respectively. In principle, the quadruple cycloaddition reactions, of two bispropargyloxycalix[4]arenes **2** with two anthracene-9,10-bis(carbonitrile oxide) **4**, should lead to a doubly bridged biscalix[4]arene **10**; however, when **2** (5.5 mM) was refluxed with **4** (5.5 mM) in THF for 24 h, the reaction mixture became very messy and was difficult to be purified by

Scheme 1. Syntheses of Biscalix[4]arenes 5, 7, and 10
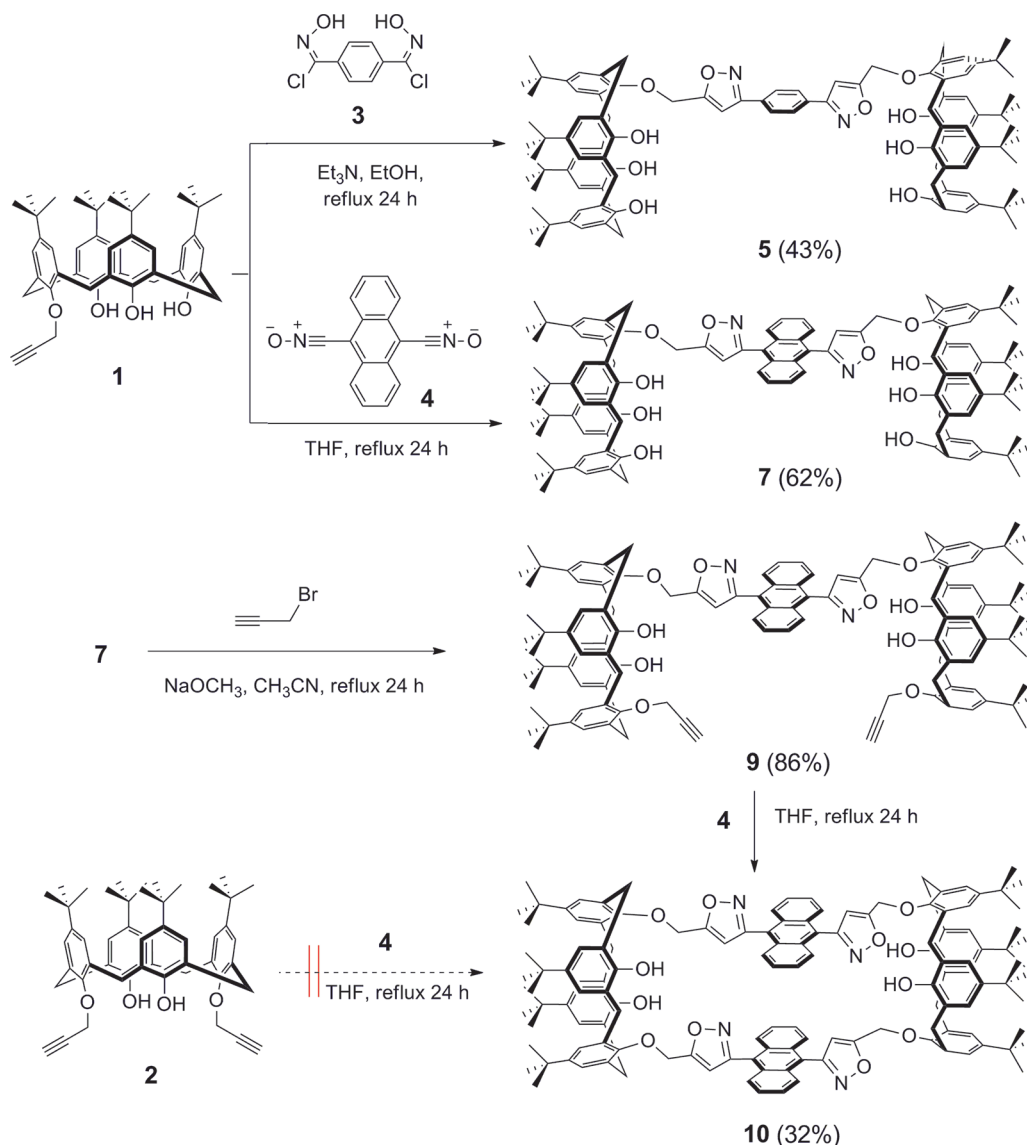
column chromatography. Alternatively, the doubly bridged biscalix[4]arene 10 could be synthesized via a two-step reaction sequence starting from 7. First, the bispropargyl ether substituted biscalix[4]arene 9 was obtained in 86% yield through S$_N$2 reaction of 7 with 2 equiv of propargyl bromide under basic conditions.

Second, a double 1,3-dipolar cycloaddition of the bispropargyl ether substituted biscalix[4]arene 9 with 4 afforded the doubly bridged biscalix[4]arene 10 in 32% yield. ^{1}H NMR spectrum of the methylene bridge protons and the isoxazole protons of biscalix[4]arene 10 showed only two singlets implying that its structure was highly symmetrical.

The N−O bond cleavage of the isoxazole units of biscalix[4]arenes 5 by Mo(CO)$_6$-mediated ring-opening reaction led to the formation of 1,4-bisketoenaminophenyl biscalix[4]arene 6 and recovered calix[4]arene in 32 and 40% yield, respectively. Under similar reaction conditions, the ring-opening reaction of 7 gave the 9,10-bisketoenaminoanthyl biscalix[4]arenes 8a and 8b, as a mixture of atropisomers, in 67% yield (Scheme 2). ^{1}H NMR spectra of these compounds showed that the amino protons of the ketoenaminos appeared

as two singlets: one around δ10.0−10.2 (due to H-bonding with the carbonyl groups) and the other around δ 5.6−5.8 ppm. The structures of all products (5−10) were fully characterized by spectral data including ^{1}H and ^{13}C NMR (Figures S12−S27, Supporting Information), mass, and high resolution mass spectrometry (Experimental Section). Furthermore, the structure of biscalix[4]arene 10 was confirmed by a single-crystal X-ray crystallography analysis (Figure 1). The X-ray crystal structure of 10 clearly shows that it contains a rectangular cone cavity. This biscalix[4]arene is a nanometer-sized macrocycle (3.0 nm long) with two parallel anthracene moieties, and the distance between the two anthracene planes is 4.0 Å. The two anthracenes are not in juxtaposition; they are slightly staggered. The cavity of 10 is constructed by the walls of two parallel anthracene moieties and two tail-to-tail calix[4]arenes; therefore, it has a potential for π−π interaction and recognition of dications by the two bridged calix[4]arenes. To this end, we envisaged that methyl viologen and its analogues may have the potential to be snugly fit into the rectangular cavity of biscalix[4]arene 10.

Scheme 2. Syntheses of Ring-Opened Biscalix[4]arene 6 and Atopisomers 8a and 8b
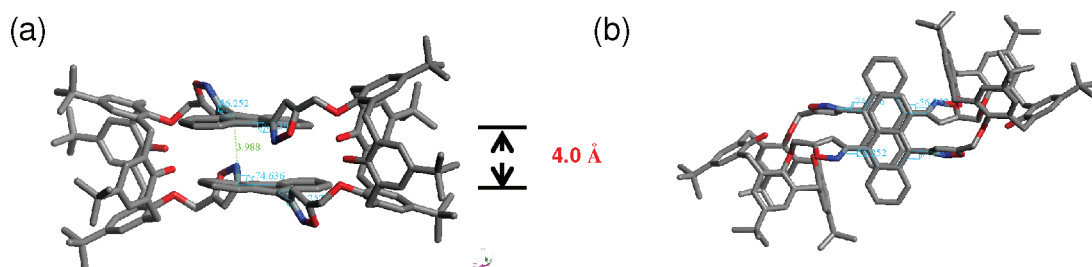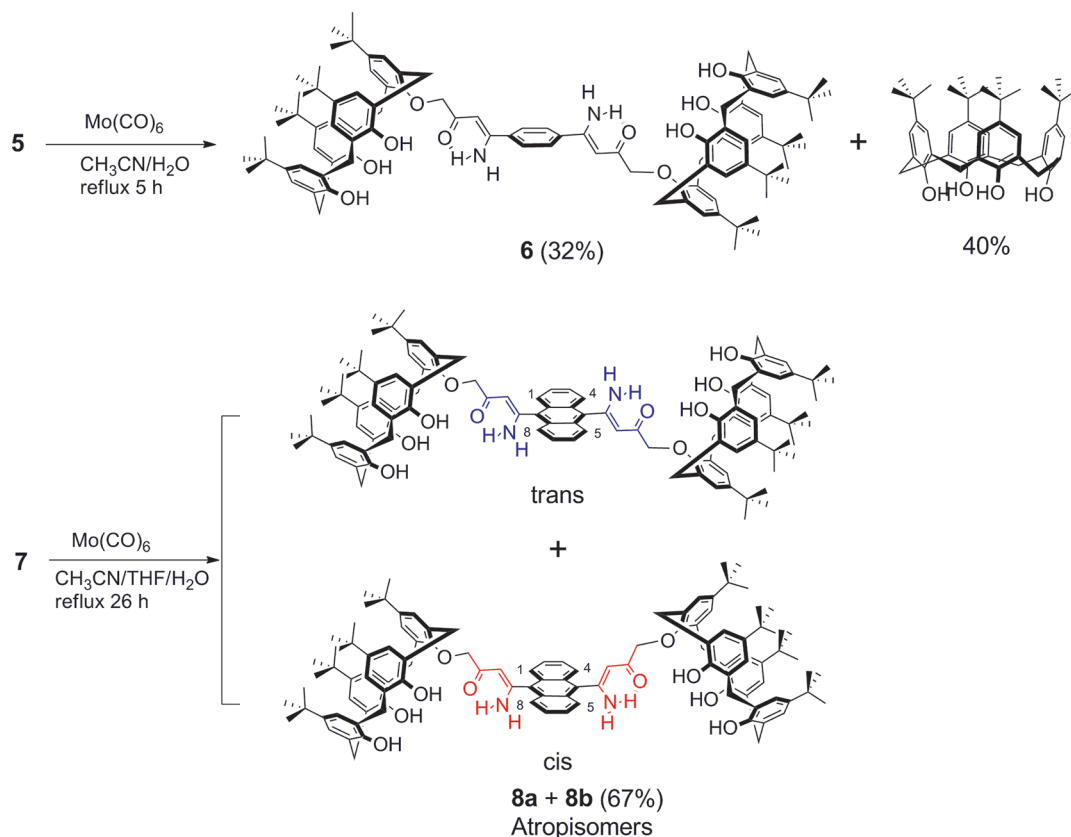
Figure 1. (a) X-ray single crystal structure of biscalix[4]arene **10** and (b) a snapshot of the structure in (a) by 90° rotation in its horizontal-axis.

Unexpectedly, the ^{1}H NMR spectra of the ring-opened products **8** clearly showed two sets of signals (Figure 2b), indicating the existence of two conformational isomers or so-called atropisomers.[15] In contrast, the ring-opened product **6**, from the reaction of 1,4-bisisoxazolylphenyl substituted biscalix[4]arene **5**, showed only one set of proton signals (Figures 2a, S1, and S2, Supporting Information).

To determine whether steric hindrance between the anthryl and the ketoenamino groups or steric bulkiness of the calix[4]arene plays the crucial role in making compounds **8** atropisomers, we synthesized a control compound **12**, in which the two calix[4]arenes were replaced by two para-t-butylphenyl ether groups (Scheme 3). The ^{1}H NMR spectrum of **12** at room temperature gives rise to two well-resolved sets of signals (Figure S26, Supporting Information). The results imply that adding a bulky substituent or not at a remote position from the 9,10-bisketoenamino substituted anthracene did not affect its atropisomeric properties. There is no need to replace t-butyloxy group with a bulkier substituent, such as calix[4]arene, to achieve atropisomeric properties in the 9,10-bisketoenamino

substituted anthracene. Note that no atropisomeric properties were found for the phenyl bridged 1,4-biscalix[4]arene **6** (Figure 2a); thus, the hindered rotation in the 9,10-bisketoenamino substituted anthracene of **8** or **12** plays a key role in forming atropisomers.

^{1}H NMR spectra of the two biscalixarenes **8a** and **8b** show that some of their signals are separated and allowed for area integrations. At room temperature (298 K), the ring-opened products **8a** and **8b** exist as a mixture of conformers with a ratio of 46:54 in CDCl$_3$ (Figures S2 and S3, Supporting Information). However, the assignment of the cis- or trans-atropisomers cannot be unambiguously determined yet. We tried to separate the atropisomers **8a** and **8b** by HPLC using various columns;[16] however, it was unsuccessful. Variable-temperature NMR studies at temperatures as high as 393 K (sample started to decompose) showed that the two sets of proton signals of **8a** and **8b** did not have any symptoms of merging (Figures S4 and S5, Supporting Information), implying a very high energy barrier for the rotations of C$_9$–C$_{11}$ and C$_{10}$–C$_{12}$ bonds.[15e,f] The energy barriers for the restricted rotation in

(a)

(b)
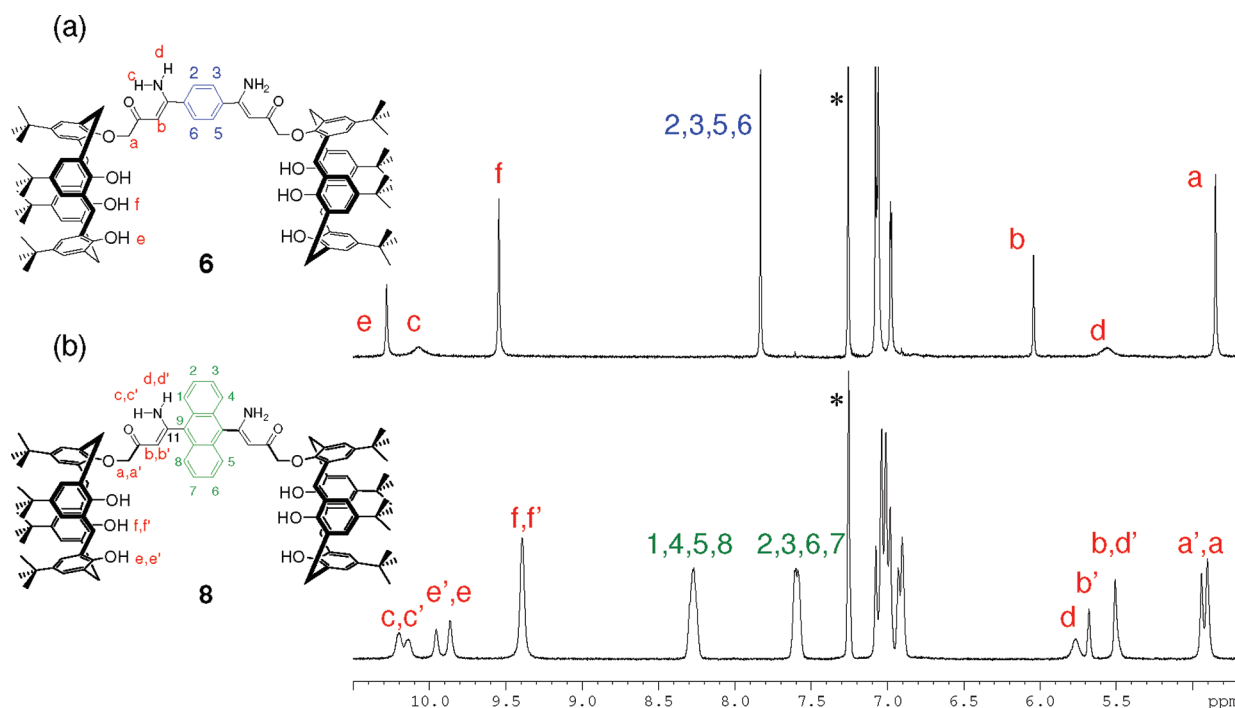
Figure 2. ^{1}H NMR spectra of the ring-opened products (a) **6** and (b) **8**, where * denotes signals from the residual of chloroform-*d*. In spectrum (b), the signals labeled with a prime come from atropisomers.

Scheme 3. Synthesis of Atropisomers 12a and 12b
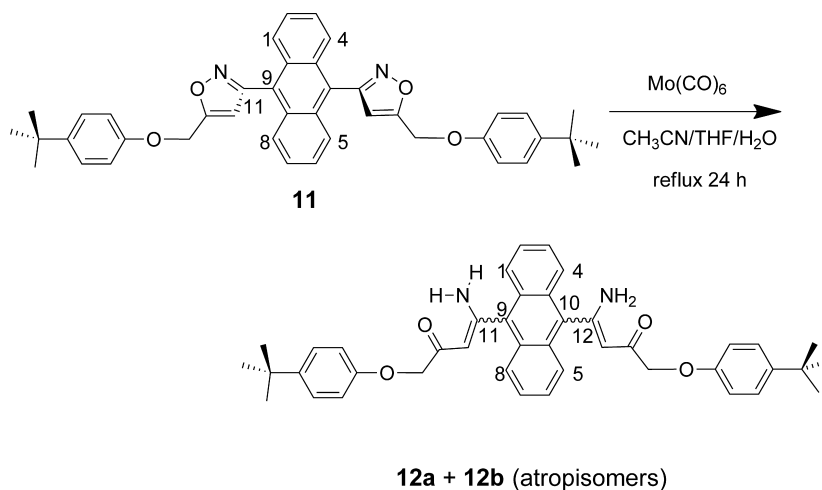
9-phenylanthracenes have been predicted by DFT calculations[15] and confirmed experimentally by VT NMR[15e,17] to be ~21 kcal mol^{-1}. On the other hand, the simplicity of the NMR spectra of **7** even at −50 °C (Figures S6, Supporting Information) implies that rapid rotation occurs at this temperature and that there is a very low energy barrier of the rotations of C$_9$–C$_{11}$ and C$_{10}$–C$_{12}$ in **7**. The rotational energy barrier of the bis-isoxazole substituted anthracene **7** is estimated to be smaller than 10 kcal mol^{-1}.[18]

The normalized fluorescence spectra of biscalix[4]arenes **7**, **10** and control compound **11** are shown in Figure 3. Biscalix[4]arene **10** displayed a broader emission band (λ_{max} at 443 nm) compared to those of biscalix[4]arene **7** and control compound **11** (both showed a λ_{max} at 432 nm). The results implied that an intramolecular π−π interaction of the two parallel anthracenes of biscalix[4]arene **10** should have

occurred in cosolvent MeOH/CHCl$_3$ (v/v, 1:2), which led to a longer emission wavelength.

Since biscalix[4]arene **10** contains anthracenes as fluorophores, we then used it in fast screening on a series of aromatic guests, alkyldiamines, and methyl viologen (**G1−G13**, Chart 1) using fluorescence spectroscopy. The binding properties of **10** in cosolvent MeOH/CHCl$_3$ (v/v, 1:2) were assessed by adding 200 equiv of various guests, and their relative fluorescence intensity changes are shown in Figure 4. There was basically no (or very small) change in the fluorescence spectra of biscalix[4]arene **10** when it was mixed with excess aromatic guests (**G1−G5**) and alkyldiamines (**G7−G13**). To our delight, only methyl viologen (**G6**) caused a significant quenching on the fluorescence of biscalix[4]arene **10** (Figures 4 and 5). The fluorescence quantum yield of **10** was determined to be 0.80 ± 0.02 using 9,10-diphenylanthracene
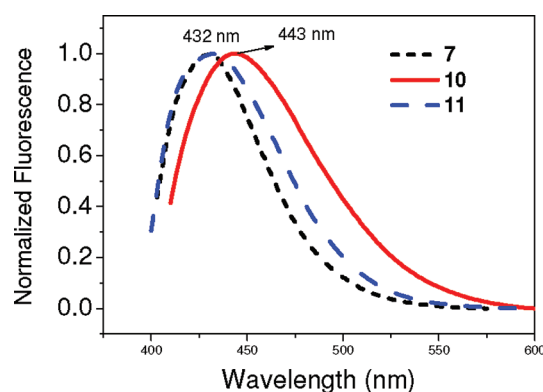
Figure 3. Normalized fluorescence spectra of biscalixarenes **7**, **10** and control compound **11** (10 μM, MeOH/CHCl$_3$ (v/v, 1:2)). Excitation wavelength was at 393 nm for **7**, 395 nm for **10**, and 392 nm for **11**.


Figure 4. Relative fluorescence intensity changes (($I - I_0$)/$I_0 \times 100\%$) of biscalixarenes **7**, **10** and the control compound **11** (each of 10 μM) in MeOH/CHCl$_3$ (v/v, 1:2) at 298 K upon addition of various guests (200 equiv). Excitation wavelength was at 393 nm for **7**, 395 nm for **10**, and 392 nm for **11**.

as a standard.[19] Upon titration with **G6**, the fluorescence intensity of **10** gradually decreased, which gave a fluorescence quantum yield of 0.57 ± 0.01 (30% decrease) at 200 equiv of **G6**. The association constant of complex **10·G6** was determined to be 137.4 ± 7.6 M^{-1} by a Stern−Volmer plot[20] (Figure 5b). Furthermore, the excimer emission of **10** was slightly blue-shifted at high equivalents of **G6**, indicating that the $\pi-\pi$ interaction of the two parallel anthracenes of biscalix[4]arene **10** was reduced. The results imply that **G6** might have been embedded into the cavity of biscalix[4]arene **10**, hence favoring the monomer emission compared to that of the excimer.

^{1}H NMR titration experiments of biscalix[4]arene **10** with methyl viologen (**G6**) were also carried out to shed light on its binding mode (see Figures S7 and S8, Supporting Information). The proton signals of the anthracene of the host **10** were slightly upfield shifted by the addition of **G6**, which is consistent with the inclusion of **G6** in the cavity of **10**. Moreover, we also found that the proton signals of **G6** were broadened and high field shifted in the presence of 10 equiv of **10** (Figure S8, Supporting Information). Diffusion-ordered NMR spectroscopy (DOSY) has been particularly useful in the characterization of complex host−guest systems in solution.[21] Thus, 2D DOSY experiments were used to investigate the complex between biscalixarene **10** and **G6**. When a 1:1 mixture of **10** and **G6** was measured in CD$_3$OD/CDCl$_3$ (v/v, 1/2) at 295 K, the diffusion coefficients for host **10** and guest **G6** were determined to be 3.16 × 10^{-10} and 6.03 × 10^{-10} m^2/s, respectively. However, when 100 equiv of **G6** with 1 equiv of **10** were measured by 2D DOSY, a new species with a different diffusion coefficient (4.17 × 10^{-10} m^2/s) appeared. This indicates that biscalixarene **10** and methyl viologen **G6** form a complex. (Figure S9, Supporting Information)
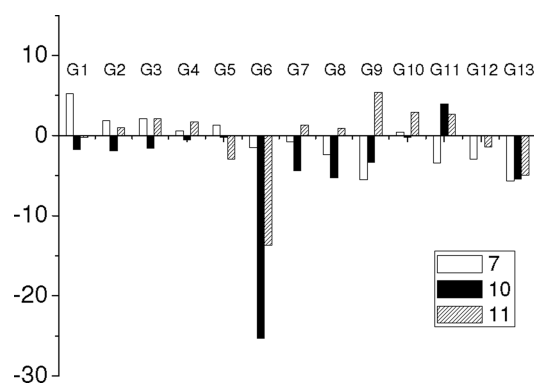
In order to know whether the rectangular cavity of biscalix[4]arene **10** is necessary for the recognition of methyl viologen, we synthesized a control compound **11**, in which the two calix[4]arene units are replaced by two *para-t*-butylphenyl groups. Furthermore, the fluorescence study of the open-chained biscalix[4]arene **7** toward methyl viologen **G6** was also used for comparison (Figure 4). The fluorescence of the open-chained biscalix[4]arene **7** showed very little change at 200 equiv of **G6**;[19] however, the fluorescence quantum yield of the other control compound **11** did show some quenching by **G6**. The quenching effect of methyl viologen **G6** on the open-chain bis-*para-t*-butylphenyl **11** was smaller (Φ_F decreased by 20%) compared to that on the biscalix[4]arene **10** (Φ_F decreased by 30%). The association constant of complex **11·G6** was determined to be 77.6 ± 0.6 M^{-1} by a Stern−Volmer plot.[20] (Figure S10, Supporting Information). The ^{1}H NMR titration spectra of control compound **11** with **G6** showed no change even with 10 equiv of **G6** (Figure S11, Supporting Information). On the basis of these observations, we conclude that not only the cation−π interaction but also a proper cavity size must have played important roles in the binding of methyl viologen (**G6**) by biscalix[4]arene **10**.

Finally, an optimized geometry of **10** with **G6** was calculated by the molecular modeling DMol^3 and simulated in CHCl$_3$ environment (Figure 6 and Tables S4−S5, Supporting Information).[22,23] The DMol^3 method from Material Studio 5.0 is developed by Accelrys Inc., in which the wave functions are expanded in terms of an accurate numerical basis set. We used a double-numeric quality basis set with polarization functions (DNP). The size of the DNP basis set is comparable to Gaussian 6-31G**, but DNP is more accurate than a
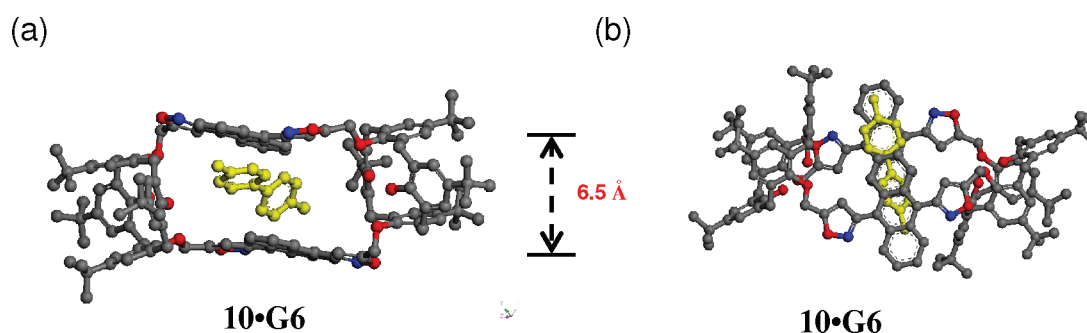
Chart 1
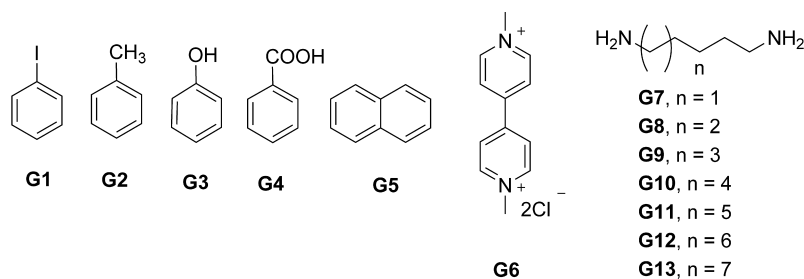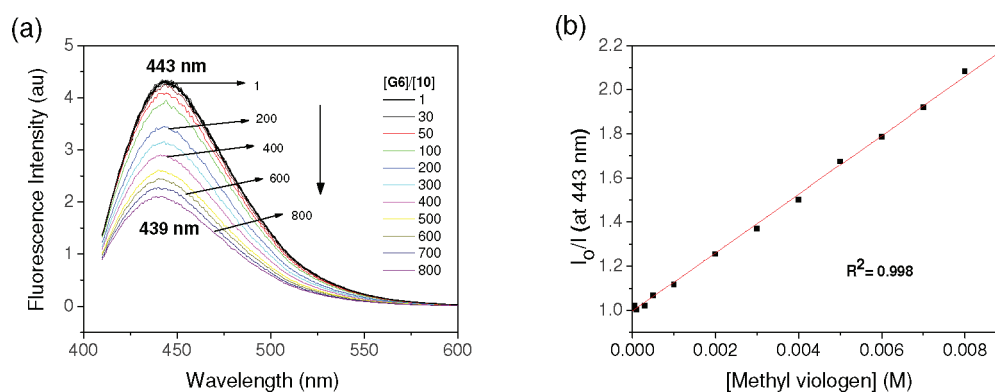
Figure 5. (a) Fluorescence emission spectra of biscalix[4]arene **10** (10 μM) in the presence of various equivalents of methyl viologen (**G6**) and (b) its corresponding Stern−Volmer plot using the intensity at 443 nm as a parameter ($K_a = 137.4 \pm 7.6$ M^{-1}). All measurements were in a cosolvent of MeOH/CHCl$_3$ (v/v, 1:2), and the excitation wavelength was 395 nm.

Figure 6. A possible binding mode of the complexation of biscalix[4]arene **10** with **G6** (a) side view and (b) top view.

Gaussian basis set of the same size.[23] The tolerances of the energy, gradient, and displacement convergences were 2 × 10^{-5} Ha, 4 × 10^{-3} Ha Å^{-1}, and 5 × 10^{-3} Å, respectively.[23b] The optimized geometries of **10** with **G6** by calculation showed a sandwich-like structure. The distance between two anthracenes of **10** increased from 4.0 Å (crystal) to ca. 6.5 Å when the **G6** was embedded into the cavity of biscalix[4]arene **10**. The results explain why the excimer emission of **10** was slightly blue-shifted.

CONCLUSION

Using a two-step reaction sequence, we have successfully synthesized a novel fluorescent biscalix[4]arene **10** with rectangular cavity. The biscalix[4]arene **10**, with two parallel anthracene units, was found to show some affinity to dication molecules such as methyl viologen (**G6**). Although the binding constant of biscalix[4]arene **10** with **G6** is small (137.4 ± 7.6 M^{-1}), it has the advantages of fast and easy screening by fluorescence spectroscopy. From a comparison of the results with two other control compounds (**7** and **11**), we believe that the cation−π interaction as well as a proper cavity size play key roles in the complexation of biscalix[4]arene **10** with **G6**. Moreover, 2D DOSY experiments provided strong evidence to support the complex formation between **10** and **G6**.

We also found that not only 9,10-bisketoenaminoanthryl biscalix[4]arenes (**8a** and **8b**) but also 9,10-bisketoenaminoanthryl bis-t-butyl-phenol ethers (**12a** and **12b**) are atropisomers, where hindered rotation between the ketoenamino group and the nearby C−H hydrogens of the anthracene were the key features. The estimated energy barriers for the restricted rotation of in the 9,10-bisketoenaminoanthryl derivatives **8a,b** are >23 kcal mol^{-1} from VT NMR. In sharp

contrast, the isoxazole substituted 9,10-bisisoxazolylanthryl biscalix[4]arene **7** has a much lower energy barrier on the rotation of C$_9$−C$_{11}$; therefore, even at temperatures as low as −50 °C, it did not show any symptom of proton NMR signal splitting between its atropisomers.

EXPERIMENTAL SECTION

General Methods. ^{1}H NMR spectra were measured with either a 300 or 500 MHz spectrometer. Natural abundance ^{13}C NMR spectra were measured using pulse Fourier transform techniques, with a 300 or 500 MHz NMR spectrometer operating at 75.4 and 125.7 MHz, respectively. Mass spectra were recorded in the FAB mode with *m*-nitrobenzyl alcohol (NBA) as the matrix. UV−vis and fluorescence spectra were measured with spectrometer and spectrofluorimeter using HPLC-grade solvents.

1,4-Bis-isoxazolyl-phenylmethyl Linked Biscalix[4]arene, 5. Triethylamine (0.35 mmol) in ethanol (1.9 mL) was slowly added to a well-stirred solution of **1** (0.40 g, 0.69 mmol) and hydroximoyl chloride **3** (0.07 g, 0.31 mmol) in ethanol (30 mL). The reaction mixture was stirred at reflux for 24 h under N$_2$ (g). After evaporation of the solvent, the mixture was washed with water and extracted with dichloromethane. The organic phase was dried over MgSO$_4$, and the solvent was removed under reduced pressure. The residue was purified by silica gel column chromatography using ethyl acetate/*n*-hexane as eluent to give 0.20 g (42.7%) of **5** as a yellow solid: mp 178−180 °C; R_f = 0.45 (ethyl acetate/*n*-hexane = 1:4); ^{1}H NMR (CDCl$_3$, 300 MHz) δ_H 10.00 (s, 2H), 9.16 (s, 4H), 8.03 (s, 4H), 7.12−6.99 (m, 16H), 5.39 (s, 4H), 4.33 (d, 4H, J = 13.2 Hz), 4.26 (d, 4H, J = 13.7 Hz), 3.46 (d, 4H, J = 13.2 Hz), 3.44 (d, 4H, J = 13.7 Hz), 1.22−1.20 (m, 72H) ppm; ^{13}C NMR (CDCl$_3$, 75.5 MHz) δ_C 167.6 (Cq), 162.1 (Cq), 149.0 (Cq), 148.9 (Cq), 148.3 (Cq), 147.5 (Cq), 143.7 (Cq), 143.2 (Cq), 133.2 (Cq), 130.4 (Cq), 128.1 (Cq), 127.7 (Cq), 127.6 (CH), 127.4 (Cq), 126.7 (CH), 125.8 (CH), 125.7 (CH), 125.6 (CH), 102.8 (CH), 68.1 (CH$_2$), 34.3 (Cq), 34.0 (Cq), 33.9 (Cq), 32.9 (CH$_2$), 32.2

(CH$_2$), 31.4 (CH$_3$), 31.2 (CH$_3$) ppm; FAB-MS m/z 1534 (M + H$^+$), 1533 (M$^+$); HRMS (FAB) calcd for C$_{102}$H$_{120}$O$_{10}$N$_2$ 1532.8943, found 1532.8916.

1,4-Bis-ketoenamino-phenylmethyl Linked Biscalix[4]arene, 6. A mixture of **5** (0.05 g, 0.03 mmol), Mo(CO)$_6$ (0.02 g, 0.08 mmol), and H$_2$O (0.2 mL) in CH$_3$CN (10 mL) was stirred and heated at reflux for 5 h. The solvent was removed under a vacuum, and the residue was dissolved in 10 mL of dichloromethane. Then, to the solution was added 10 mL of NH$_4$OH (aq) to remove remaining molybdenum salts. After stirring for 1 h, the organic layer was washed with water and 1 M EDTA (aq). The organic phase was dried over MgSO$_4$, and the solvent was removed under reduced pressure. The residue was purified by neutral silica gel column chromatography with ethyl acetate/n-hexane (v/v, 1:5) as eluent to give 0.016 g (31.9%) of yellow solid **6** with *para-tert*-butyl calix[4]arene (40%) as a side product. **6**: mp 182−184 °C; R_f = 0.1 in ethyl acetate/n-hexane (v/v, 1:3); ^{1}H NMR (300 MHz, CDCl$_3$) δ_H 10.28 (s, 2H), 10.07 (bs, 2H), 9.55 (s, 4H), 7.83 (s, 4H), 7.09−6.98 (m, 16H), 6.04 (s, 2H), 5.56 (bs, 2H), 4.85 (s, 4H), 4.53 (d, 4H, J = 12.9 Hz), 4.29 (d, 4H, J = 13.8 Hz), 3.44 (d, 4H, J = 13.5 Hz), 3.41 (d, 4H, J = 12.9 Hz), 1.50−1.36 (m, 72H) ppm; ^{13}C NMR (CDCl$_3$, 75.5 MHz) δ_C 193.6 (Cq), 161.7 (Cq), 150.3 (Cq), 148.3 (Cq), 148.0 (Cq), 143.5 (Cq), 143.0 (Cq), 139.2 (Cq), 133.4 (Cq), 128.2 (Cq), 127.4 (Cq), 127.3 (CH), 126.5 (CH), 125.8 (CH), 125.6 (CH), 91.1 (CH), 79.2 (CH$_2$), 34.2 (Cq), 34.0 (Cq), 33.9 (Cq), 33.1 (CH$_2$), 32.3 (CH$_2$), 31.5 (CH$_3$), 31.2 (CH$_3$) ppm; FAB-MS m/z 1539 (M + 2), 1538 (M + H$^+$); HRMS (FAB) calcd for C$_{102}$H$_{124}$N$_2$O$_{10}$ 1536.9256, found 1536.9266.

9,10-Bis-isoxazolylanthryl-methyl Linked Biscalix[4]arene, 7. A mixture of **1** (0.20 g, 0.30 mmol) and **4** (0.04 g, 0.15 mmol) in THF (15 mL) was heated at reflux for 24 h under N$_2$ (g). After evaporation of the solvent, the mixture was washed with water and extracted with dichloromethane. The organic phase was dried over MgSO$_4$, and the solvent was removed under reduced pressure. The residue was purified by silica gel column chromatography with ethyl acetate/n-hexane as eluent to give 0.15 g (62.2%) of **7** as a yellow solid: mp 180−182 °C; R_f = 0.35 (ethyl acetate/n-hexane (v/v, 1:5)); ^{1}H NMR (300 MHz, CDCl$_3$) δ_H 10.13 (s, 2H), 9.34 (s, 4H), 8.11−8.08 (m, 4H), 7.61−7.58 (m, 4H), 7.28−7.07 (m, 18H), 5.63 (s, 4H), 4.55 (d, 4H, J = 13.2 Hz), 4.33 (d, 4H, J = 13.8 Hz), 3.61 (d, 4H, J = 13.2 Hz), 3.51 (d, 4H, J = 13.8 Hz), 1.33−1.29 (m, 72H) ppm; ^{13}C NMR (CDCl$_3$, 75.5 MHz) δ_C 167.2 (Cq), 161.4 (Cq), 149.1 (Cq), 148.8 (Cq), 148.3 (Cq), 147.7 (Cq), 143.6 (Cq), 143.3 (Cq), 133.5 (Cq), 130.3 (Cq), 128.1 (Cq), 127.7 (Cq), 127.7 (Cq), 126.8 (CH), 126.0 (CH), 125.9 (CH), 125.7 (CH), 125.7 (CH), 125.5 (Cq), 108.8 (CH), 67.6 (CH$_2$), 34.3 (Cq), 34.0 (Cq), 33.9 (Cq), 32.9 (CH$_2$), 32.4 (CH$_2$), 31.5 (CH$_3$), 31.2 (CH$_3$) ppm; FAB-MS m/z 1634 (M + H$^+$), 1633 (M$^+$); HRMS (FAB) calcd for C$_{110}$H$_{124}$O$_{10}$N$_2$ 1632.9256, found 1632.9275.

9,10-Bis-ketoenaminoanthryl Linked Biscalix[4]arene, 8. A mixture of **7** (0.10 g, 0.06 mmol), Mo(CO)$_6$ (0.07 g, 0.25 mmol), and 3 drops H$_2$O in THF/CH$_3$CN (1 mL/10 mL) was stirred and heated at reflux for 5 h. The solvent was removed under a vacuum, and the residue was dissolved in 10 mL of dichloromethane. Then, to the solution was added 10 mL of NH$_4$OH (aq) to remove remaining molybdenum salts. After stirring for 1 h, the organic layer was washed with water and 1 M EDTA (aq). The organic phase was dried over MgSO$_4$, and the solvent was removed under reduced pressure. The residue was purified by neutral silica gel column chromatography with ethyl acetate/n-hexane (v/v, 1/5) as eluent to give 0.07 g (66.7%) of yellow solid **8a** and **8b** (atropisomers): mp 218−220 °C; R_f = 0.43 (ethyl acetate/n-hexane (v/v, 1:3)); ^{1}H NMR (300 MHz, CDCl$_3$) atropisomers 25 °C, area ratio = 46:54, δ_H 10.20 (bs, 1H), 10.14 (bs, 1H), 9.96 (s, 2H), 9.87 (s, 2H), 9.39 (s, 4H), 8.28−8.27 (m, 4H), 7.61−7.59 (m, 4H), 7.08−6.90 (m, 16H), 5.76 (bs, 1H), 5.68 (s, 1H), 5.51 (s, 2H), 4.94 (s, 2H), 4.90 (s, 2H), 4.60−4.44 (m, 4H), 3.99−3.91 (m, 4H), 3.42−3.21 (m, 8H) 1.23−1.19 (m, 72H) ppm; ^{13}C NMR (75.5 MHz) δ_C 207.1 (Cq), 193.5 (Cq), 193.2 (Cq), 161.5 (Cq), 161.2 (Cq), 150.9 (Cq), 150.6 (Cq), 148.2 (Cq), 148.1, (Cq), 148.1 (Cq), 147.9 (Cq), 147.7 (Cq), 143.3 (Cq), 143.2 (Cq), 142.9 (Cq), 133.6 (Cq), 133.5 (Cq), 132.8 (Cq), 132.7 (Cq), 128.2 (Cq), 128.1 (Cq), 127.9 (Cq), 127.8 (Cq), 127.5 (Cq), 127.5 (Cq), 127.0 (CH), 126.9

(CH), 126.4 (CH), 126.3 (CH), 125.9 (CH), 125.8 (CH), 125.5 (CH), 95.3 (CH), 94.7 (CH), 78.9 (CH$_2$), 78.7 (CH$_2$), 78.2 (CH$_2$), 34.1 (Cq), 33.9 (Cq), 33.9 (Cq), 33.9 (Cq), 33.0 (Cq), 32.7 (CH$_2$), 32.6 (CH$_2$), 32.4 (CH$_2$), 31.5 (CH$_3$), 31.4 (CH$_3$), 31.2 (CH$_3$), 30.9 (CH$_3$), 29.7 (CH$_2$) ppm; FAB-MS m/z 1638 (M + H$^+$), 1637 (M$^+$); HRMS (FAB) calcd for C$_{110}$H$_{128}$N$_2$O$_{10}$ 1636.9569, found 1636.9586.

Bispropargyl Ether Substituted 9,10-Bis-isoxazolylanthryl-methyl Linked Biscalix[4]arene, 9. A mixture of **7** (0.11 g, 0.07 mmol), sodium methoxide (0.01 g, 0.18 mmol), and propargyl bromide (0.04 mL, 0.34 mmol) in CHCl$_3$/CH$_3$CN (3 mL/30 mL) was stirred and heated at reflux for 24 h. The solvent was removed under a vacuum, and the residue was purified by silica gel column chromatography with ethyl acetate/n-hexane as eluent to give 0.10 g (85.8%) of **9**: mp 239−241 °C; R_f = 0.18 (ethyl acetate/n-hexane = 1:5); ^{1}H NMR (300 MHz, CDCl$_3$) δ_H 8.00−7.96 (m, 4H), 7.51−7.48 (m, 4H), 7.25−6.74 (m, 22H), 5.40 (s, 4H), 4.54 (d, 4H, J = 2.3 Hz), 4.36 (d, 4H, J = 13.2 Hz), 4.31 (d, 4H, J = 13.4 Hz), 3.39 (d, 4H, J = 13.2 Hz), 3.32 (d, 4H, J = 13.4 Hz), 2.13 (t, 2H, J = 2.3 Hz), 1.30−1.15 (m, 72H) ppm; ^{13}C NMR (75.5 MHz) δ_C 168.5 (Cq), 161.0 (Cq), 150.4 (Cq), 149.5 (Cq), 149.3 (Cq), 147.6 (Cq), 147.5 (Cq), 141.7 (Cq), 132.6 (Cq), 132.4 (Cq), 130.2 (Cq), 127.8 (Cq), 127.8 (Cq), 126.6 (CH), 126.1 (CH), 125.8 (CH), 125.7 (Cq), 125.6 (CH), 125.1 (CH), 107.9 (CH), 78.2 (Cq), 76.2 (Cq), 68.2 (CH$_2$), 63.3 (CH$_2$), 37.1 (Cq), 33.9 (Cq), 33.8 (Cq), 32.1 (CH$_2$), 31.9 (CH$_2$), 31.7 (CH$_3$), 30.9 (CH$_3$) ppm; FABMS m/z 1709 (M + 2), 1708 (M + H$^+$), 1707 (M$^+$); HRMS calcd for C$_{116}$H$_{128}$O$_{10}$N$_2$ 1708.9569, found 1708.9546.

Doubly Bridged 9,10-Bis-isoxazolylanthryl Substituted Biscalix[4]arene, 10. A mixture of **9** (0.10 g, 0.05 mmol) and **4** (0.02 g, 0.06 mmol) in THF (15 mL) was stirred and heated at reflux for 24 h under N$_2$ system. The solvent was removed under a vacuum, and the residue was purified by silica gel column chromatography with ethyl acetate/n-hexane as eluent to give 0.04 g (32.2%) of biscalix[4]arene **10** as a yellow solid: mp > 260 °C (decomposed); R_f = 0.23 (ethyl acetate/n-hexane (v/v, 1:4)); ^{1}H NMR (300 MHz, CDCl$_3$) δ_H 7.72−7.69 (m, 8H), 7.32−7.11 (m, 8H), 6.94 (s, 8H), 6.32 (s, 4H), 5.24 (s, 8H), 4.37 (d, 8H, J = 13.2 Hz), 3.47 (d, 8H, J = 13.2 Hz), 1.28 (s, 36H), 1.08 (s, 36H) ppm; ^{13}C NMR (75.5 MHz) δ_C 168.2 (Cq), 160.6 (Cq), 150.5 (Cq), 149.8 (Cq), 147.9 (Cq), 141.9 (Cq), 132.6 (Cq), 129.8 (Cq), 127.5 (Cq), 126.4 (CH), 126.0 (CH), 125.8 (CH), 125.3 (CH), 125.2 (Cq), 107.1 (CH), 68.2 (CH$_2$), 34.1 (Cq), 33.9 (Cq), 32.0 (CH$_2$), 31.7 (CH$_3$), 31.0 (CH$_3$) ppm; FAB-MS m/z 1970 (M + H$^+$); HRMS (FAB) calcd for C$_{132}$H$_{136}$O$_{12}$N$_4$ 1969.0155, found 1969.0137.

X-ray Crystal Data for 10. C$_{137}$H$_{155}$Cl$_3$N$_4$O$_{16}$; M = 2220.00; T = 150(2) K; triclinic; a = 11.9430(8) Å, b = 16.0684(10) Å, c = 16.8946(8) Å; α = 82.311(4)°, β = 81.842(5)°, γ = 78.038(5)°; V = 3121.4(3) Å^3; space group P$\bar{1}$; Z = 1; ρ_{calcd} = 1.181 mg m^{-3}; crystal dimensions 0.20 × 0.15 × 0.10 mm^3; λ = 1.54178 Å; 29213 reflections collected; 11277 independent reflections [R_{int} = 0.0379]; absorption coefficient 1.176 mm^{-1}; 1184 parameter refined on F^2; R_1 = 0.1173, wR_2 [F^2] = 0.3066 (all data); GOF on F^2 = 2.333; $\Delta\rho_{max}$ = 1.774 e Å^{-3}. CCDC-853852 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

3,3′-Anthracene-9,10-diylbis{5-[4-*tert*-butylphenoxy)-methyl]isoxazole}, 11. A mixture of 1-*tert*-butyl-4-(prop-2-ynyloxy)-benzene (0.20 g, 1.07 mmol) and **4** (0.12 g, 0.48 mmol) in THF (25 mL) was stirred and heated at reflux for 24 h under a N$_2$ system. The solvent was removed under a vacuum, and the residue was purified by silica gel column chromatography with ethyl acetate/n-hexane as eluent to give 0.16 g (52.1%) of **11** as a yellow solid: mp 231−233 °C; R_f = 0.45 (ethyl acetate/n-hexane (v/v, 1:4)); ^{1}H NMR (300 MHz, CDCl$_3$) δ_H 7.88−7.85 (m, 4H), 7.49−7.45 (m, 4H), 7.38 (d, 4H, J = 8.7 Hz), 7.00 (d, 4H, J = 8.7 Hz), 6.64 (s, 2H), 5.37 (s, 4H), 1.31 (s, 18H) ppm; ^{13}C NMR (75.5 MHz, CDCl$_3$) δ_C 168.9 (Cq), 160.8 (Cq), 155.5 (Cq), 144.7 (Cq), 130.1 (Cq), 126.5 (CH), 125.9 (CH), 125.5 (Cq), 114.4 (CH), 106.8 (CH), 61.7 (CH$_2$), 34.1 (Cq), 31.5 (CH$_3$)

ppm; FABMS m/z 637 (M + H$^+$), 636 (M$^+$); HRMS calcd for $C_{42}H_{40}O_4N_2$ 636.2988, found 636.2994.

(3Z,3′Z)-4,4′-Anthracene-9,10-diylbis[4-amino-1-(4-*tert*-butylphenoxy)but-3-en-2-one], 12a−b. A mixture of **11** (0.07 g, 0.11 mmol), Mo(CO)$_6$ (0.07 g, 0.25 mmol) and H$_2$O (0.2 mL) in THF/CH$_3$CN (1 mL/10 mL) was stirred and heated at reflux for 24 h. The solvent was removed under a vacuum, and the residue was dissolved in 10 mL of dichloromethane. Then, to the solution was added 10 mL of NH$_4$OH (aq) to remove remaining molybdenum salts. After stirring for 1 h, the organic layer was washed with water and 1 M EDTA (aq). The organic phase was dried over MgSO$_4$, and the solvent was removed under reduced pressure. The residue was purified by neutral silica gel column chromatography with ethyl acetate/*n*-hexane (1/5) as eluent to give trace amount of yellow solid **12** (atropisomers): mp > 180 °C (decomposed); R_f = 0.20 (ethyl acetate/*n*-hexane (v/v, 1:3)); ^{1}H NMR (300 MHz, CDCl$_3$) δ_H 10.44 (bs, 2H), 8.11−8.07 (m, 4H), 7.61−7.46 (m, 4H), 7.28−7.25 (m, 2H), 6.91−6.79 (m, 2H), 5.82 (s, 1H), 5.78 (s, 1H), 5.50 (bs, 1H) 5.43 (bs, 2H), 4.63, (s, 2H), 4.62 (s, 4H), 1.28−1.26 (m, 9H) ppm; ^{13}C NMR (75.5 MHz, CDCl$_3$) δ_C 195.6 (Cq), 195.6(Cq), 161.0 (Cq), 160.9(Cq), 155.9 (Cq), 143.8 (Cq), 132.8 (Cq), 127.9(Cq), 126.8 (CH), 126.2 (CH), 125.6 (CH), 114.0 (CH), 95.8 (CH), 72.0 (CH$_2$), 34.1 (Cq), 31.5 (CH$_3$) ppm; HRMS (FAB) calcd for $C_{42}H_{40}N_2O_4$ 636.2988, found 636.2994.

ASSOCIATED CONTENT

ⓢ Supporting Information

Crystallographic data for compound **10** (CIF), data calculated by molecular modeling using DMol^3 for the optimized geometry of complex **10·G6**, ^{1}H and ^{13}C NMR spectra for all products **5−12**, and spectroscopic 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.

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(16) Normal phase HPLC was performed with a Gilson 321-H1 pump system with a 506C interface, a Rheodyne 7725I injector, a Gilson 155 UV−vis detector (Gilson, Inc., Middleton, WI). For silica column (Hypersil, 4.6 × 250 mm, 5 μm), the mobile phase was eluted from hexane to hexane/EA (v/v, 2:3) over 30 min at a flow rate of 1 mL/min. For CHIRALPAK AS-H and CHIRACEL OD-H columns (both are 4.6 × 250 mm, 5 μm, Daicel Chemical Industrial, Ltd., Tokyo), the mobile phase of 2-propanol/hexane (v/v, 1:9) was eluted isocratically at a flow rate of 0.5 mL/min.

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(18) The rotation barrier was calculated on the basis of the variable temperature NMR experiment using the equation in ref 15g.

(19) The relative fluorescence quantum yields were determined by comparison of the integrated area of the emission spectra of the samples with the reference compound 9,10-diphenylanthracene (Φ_F = 0.90 ± 0.02 in cyclohexane). For the guest-free studies, biscalixarenes **7**, **10** and control compound **11** were at 10 μM concentration in MeOH/CHCl$_3$ (v/v, 1:2). For the complexation studies, 200 equiv of **G6** (methyl viologen) was added to 10 μM solution of biscalixarenes **7**, **10** or control compound **11** in MeOH/CHCl$_3$ (v/v, 1:2). Emission spectra of these samples were integrated from 390 to 650 nm with

excitation at 388 nm for **7** and 384 for **11** and from 395 to 650 nm for **10** with excitation at 391 nm. The relative fluorescent quantum yield for **7**, **10**, and **11** are 0.70 ± 0.02, 0.80 ± 0.02, and 0.96 ± 0.02, respectively. The relative quantum yields were calculated using equation: $\Phi_F = (A_{ref}/A) \times (F/F_{ref}) \times (n^2_{chloroform}/n^2_{cyclohxane}) \times \Phi_{ref}$ where A is the absorbance at the excitation wavelength, F is the integrated emission area, and n is the refractive index of the solvent ($n_{chloroform} = 1.4459$, $n_{cyclohexane} = 1.4262$ at 25 °C). See related references: (a) Eaton, D. F. *Pure Appl. Chem.* **1988**, *60*, 1107. (b) Dawson, W. R.; Windsor, M. W. *J. Phys. Chem.* **1968**, *72*, 3251.

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