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A Pyrenyl-Appended Triazole-Based Calix[4]arene as a Fluorescent Sensor for Cd^{2+} and Zn^{2+}

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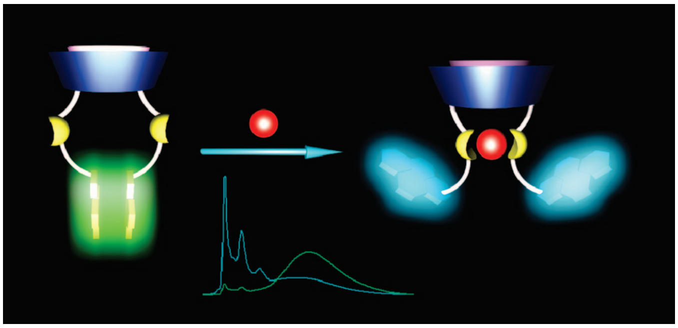

The synthesis and evaluation of a novel calix[4]arene-based fluorescent chemosensor **8** for the detection of Cd^{2+} and Zn^{2+} is described. The fluorescent spectra changes observed upon addition of various metal ions show that **8** is highly selective for Cd^{2+} and Zn^{2+} over other metal ions. Addition of Cd^{2+} and Zn^{2+} to the solution of **8** results in ratiometric measurement.

Introduction

Cadmium has found extensive uses in the fields of Ni−Cd batteries, phosphate fertilizers, pigments, and semiconducting quantum dots and rods.[1] The detrimental effects of cadmium on human health are, however, being increasingly recognized: chronic cadmium exposure can cause renal dysfunction, calcium metabolism disorders, and an increased incidence of certain forms of cancer,[2] possibly due to direct inhibition of DNA mismatch repair.[3] In addition, zinc is, after iron, the second most abundant transition metal in mammals,[4] where it plays important roles in various biological processes such as neurotransmission, signal transduction and gene expression.[5,6] Due to their toxic effects, it is important to be able to monitor the presence of cadmium and zinc quantitatively. As a result, in recent years, interest in both cadmium[7] and zinc[8] sensors has been extensive.

More generally, the sensing of metal ions with selective analytical reagents remains a challenge for environmental and biological applications.[9] With the advent of supramolecular chemistry, the design and synthesis of optically responsive chemical sensors for specific detection of metal ions has become

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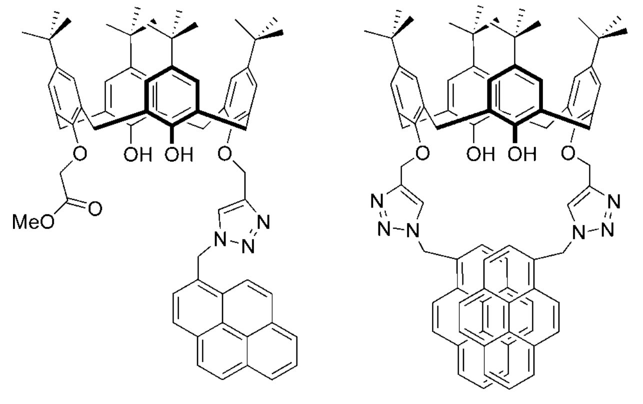
a growing field of research.[10] A chemical sensor generally includes two components, a reporter unit, for example a fluorophore, and an ionophore, which can be either independent species or covalently linked in one molecule, and additionally a mechanism for communication between them.[11] When the analytes bind to the recognition center, changes occur in the optical properties (e.g., enhancement or inhibition of absorption or fluorescence) of the chemosensor. Fluorophores are particularly attractive optical molecules and have recently found applications in self-assembled chemosensors,[12] for signal amplification by allosteric catalysis,[13] in supramolecular analytical chemistry,[14] and as fluorescent and photochromic chemosensors.[15]

The majority of fluorescent chemosensors for cations are composed of a cation recognition unit (ionophore) together with a fluorogenic unit (fluorophore) and are thus described as fluoroionophores.[10b] An effective fluorescence chemosensor must convert the event of cation recognition by the ionophore into an easily monitored and highly sensitive light signal from the fluorophore.[16] As fluorogenic units, pyrenes (Py) are one of the most useful tools due to their relatively efficient excimer formation and emission.[17] Host molecules with more than one pyrenyl group exhibit intramolecular excimer emission by two different mechanisms. One results from $\pi-\pi$ stacking of the pyrene rings in the free state, which results in a characteristic decrease of the excimer emission intensity and a concomitant increase of monomer emission intensity. The other mechanism is due to the interaction of an excited pyrene (Py*) unit with a ground state pyrene (Py) unit.[18]

The choice of ionophore is crucial for the development of an effective sensor and many systems have been developed including a range of macrocycles. Since their characterization and isolation by Gutsche et al.[19] in the 70s, the cyclooligomeric phenols known as calixarenes[20] have received much interest as basic molecular platforms for the construction of desired molecular architectures.[21] The chemistry of calixarenes is well developed and their unique topology offers a wide range of scaffolds enabling them to encapsulate many different metal ions.[21] More recently, functionalized calix[4]arenes have been incorporated into a large variety of fluorescent ion sensors.[22] In particular Broan reported that a calixarene containing pyrenyl ester groups forms an intramolecular excimer due to strong $\pi-\pi$ interaction between two pyrene units.[23] Additionally we have previously incorporated pyrene reporter molecules onto single calixarenes as the pyrene-amide and demonstrated that selective fluorescent cation sensors for Cu^{2+} and Pb^{2+} could be developed based on platforms fixed in the cone conformation[24] and K^+/Pb^{2+} on−off switchable sensors[18b] when a calix[4]crown fixed in the 1,3-alternate conformation was used. With tricalix[4]arene systems, featuring three pyrene moieties, Al^{3+} selectivity has been observed.[25] In addition, incorporation of both pyrene-amide, as a donor, and rhodamine, as an acceptor, on a dicalix[4]arene enabled the development of a mercury-induced Förster resonance energy transfer (FRET) sensor.[26]



7 **8**

FIGURE 1. Structures of fluorescent sensors **7** and **8**.

In this paper, we report the synthesis and the fluorometric properties of two pyrenyl appended calix[4]arenes **7** and **8** featuring 1,2,3-triazole linkers (Figure 1). The selective sensing

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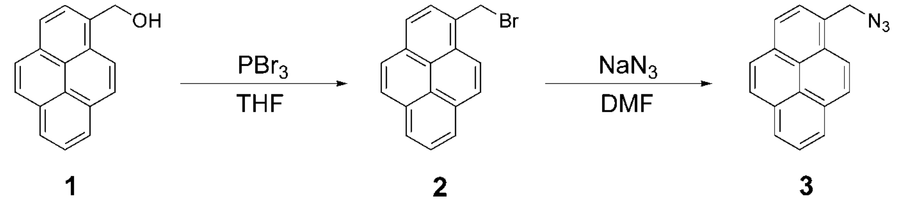
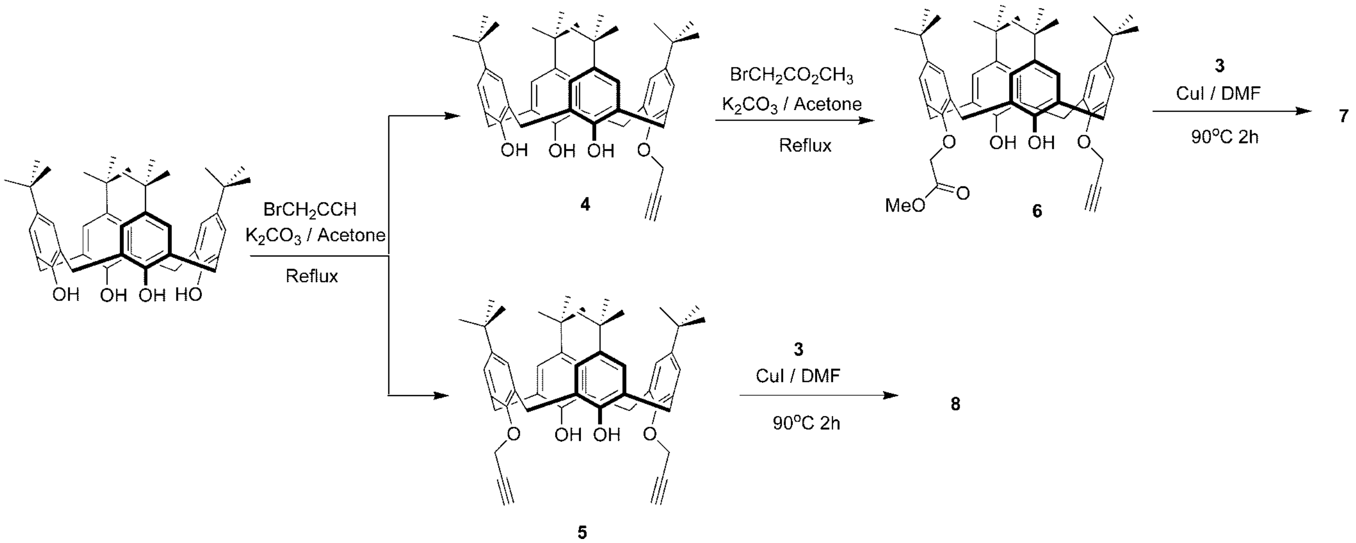
SCHEME 1. Syntheses of 2 and 3



SCHEME 2. Syntheses of 7 and 8



capability of **8** for cadmium and zinc ions, over a wide range of competing cations, with respect to ratiometric fluorescent signals is described.

Results and Discussion

Since the observation by Sharpless[27] and Meldal[28] that the Huisgen[29] 1,3-dipolar cycloaddition of alkynes and azides to give 1,2,3-triazoles can be catalyzed by Cu(I) to give exclusively the 1,4-disubstituted steroisomer the use of "click" chemistry as a straightforward linking strategy has been exploited in a wide variety of areas including bioconjugation,[30] drug design,[31] and materials chemistry.[30,32] In addition the properties of the linker in multivalent derivatives can be exploited for the binding of cations, a property first identified and developed for the accelerated catalysis of the "click" reaction itself by in situ formation of copper complexes.[33] More recently triazole-based phosphine[34] catalysts for Pd-Suzuki−Miyaura cross-couplings and Zn-triazole functionalized resins for enantioselective phenylation of aldehydes[35] have been developed. The coordination chemistry of triazoles has also been investigated through the formation of Fe^{2+}, Ru^{2+}, Re^{+}, and Eu^{3+} complexes of a range of bis-triazoles.[36] These cation binding properties of triazoles have been shown to be of potential in the radiolabeling of biomolecules[37] and the preparation of platinum-based anticancer agents.[38] Electrochemical sensing of Pt^{2+} and Pd^{2+} has been achieved with triazole functionalized dendrimers[39] whereas fluorescent probes[40] have been developed for Zn^{2+}.

The copper-catalyzed triazole click reaction has, to date, been little exploited for the functionalization of the calixarene scaffold. Since the first report[41] in 2005 on the synthesis of water-soluble derivatives through the incorporation of polyhydroxyl groups and sulfonates most reports have focused on the preparation of calix[4] sugars through azide functionalized calix[4]arene intermediates.[42] More relevant to this work are the reports of Chung and co-workers who have developed Ca^{2+} and Pb^{2+} chromogenic selective sensors through the introduction of triazole binding sites to the lower rim of calix[4]arene[43] and on−off switchable fluorescent sensors based on a calix[4]crown

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fixed in the 1,3 alternate conformation.[44] Additionally a tris upper-rim triazole functionalized calix[6]arene has been described recently that is able to coordinate Zn^{2+}.[45]

To prepare the pyrenyl-appended calix[4]arenes we functionalized *p-tert*-butylcalix[4]arene with terminal alkyne groups and treated this with an azidopyrene that allows the formation of intramolecular 1,2,3-triazole cation-binding linkers. The synthesis of 1,2,3-triazole calixarenes **7** and **8** is shown in Scheme 2.

To incorporate the reporter unit through a triazole cation binding site, the azido derivative of pyrene was prepared in a short synthetic sequence from the commercially available pyrenemethanol. The alcohol was initially converted to the bromo derivative **2** in 82% yield, using PBr_3 in dry THF. Subsequently the azide **3** was prepared in 91% yield by treatment of **2** with sodium azide (Scheme 1). As significant decomposition of **3** was observed over time, the azido derivative was freshly prepared and immediately used before each coupling reaction.

It is interesting to note that the pyrene azide reporter unit has not been previously used in the formation of triazole-based sensors; however, a very recent report[46] has described the synthesis of dialkyne pyrene derivatives which have been further functionalized as phosphoamidites for inclusion into oligonucelotides.

The synthesis of both the mono-**4**[47] and dipropargyl **5**[48] derivatives of *p-tert*-butylcalix[4]arene have previously been described. A new synthetic route was developed, as part of this synthesis, which allowed the isolation of both **4** and **5**, in acceptable yields, from a single one-pot reaction by treatment of *p-tert*-butylcalix[4]arene with an excess of propargyl bromide in the presence of 0.86 equiv of potassium carbonate. Elution of the reaction residue on silica gel with 1:1 cyclohexane/CH_2Cl_2 as eluent gave **4** (36% yield) and additionally the dialkyne **5** (23% yield). Data of **4** and **5** were consistent with materials previously prepared. The introduction of the additional carbonyl cation binding site in **7** was acheived through selective alkylation of **5** with 1 equiv of methylbromoacetate in the presence of K_2CO_3 to give the intermediate calixarene **6** in 33% yield.

The synthesis of the triazole calix[4]arene **8** was initially attempted by using previously described conditions[43] involving catalysis by CuI in a THF/H_2O mixed solvent system stirred at 50 °C. While after this time some of the desired material had been formed, more effective synthesis was achieved through alteration of the solvent to DMF, in which both reagents were freely soluble, and acceptable yields were achieved, for both **7** (56%) and **8** (57%), after stirring at 90 °C for 2 h. All the calixarenes **5**−**8** were fully characterized by NMR, MALDI-TOF mass spectrometry, and elemental analysis (Supporting Information, Figures S5−S13).

The conservation of the original fixed cone conformation of the calix[4]arene was confirmed by the presence of doublets for the ArCH_2Ar protons at ~3 and 4 ppm. The formation of the 1,2,3-triazole rings was apparent from the appearance of the triazole-*H* signal as a singlet within the range 8.00−8.50 ppm for **7** and 7.55 ppm for **8** and the downfield shift of the OCH_2-triazole linker (Supporting Information, Figures S8 and S11). The cone conformation of **8** was also confirmed by the determination of its X-ray crystal structure (Supporting Information, Figure S14).

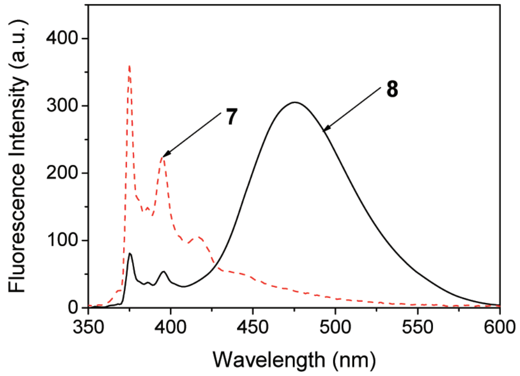

FIGURE 2. Fluorescence spectra of **7** and **8** (6.0 μM) in CH_3CN. The excitation wavelength is 343 nm.

The optical properties of both **8**, featuring two triazole binding sites, and **7**, which incorporates a single triazole binding site and an additional carbonyl moiety, known for binding of group 1 metals, were studied. On excitation at 343 nm, the maximum absorption wavelength of the pyrene in **8** displays both monomer and excimer emissions at 395 and 476 nm, respectively, whereas in **7** only a monomer emission is observed at 395 nm (Figure 2). It is notable that the formation of the excimer emission in **8** is caused by an intramolecular interaction between Py (the ground state pyrene) and Py* (the photoinduced excited state pyrene)[18] where two pyrenes are likely to be in parallel, which is quite constant with the results from X-ray crystal analysis (vide supra).

To obtain an insight into the binding properties of **7** and **8** toward metal ions, we investigated the fluorescence changes upon addition of the perchlorate salt of a wide range of cations including Li^+, Na^+, K^+, Rb^+, Cs^+, Mg^{2+}, Ca^{2+}, Sr^{2+}, Ba^{2+}, Ag^+, Cu^{2+}, Zn^{2+}, Cd^{2+}, Hg^{2+}, and Pb^{2+} in CH_3CN. The fluorescence changes are depicted in Figure 3. Addition of Zn^{2+} or Cd^{2+} ion to the CH_3CN solution of **8** bearing pyrene-triazoles as a metal ligating group induced a remarked ratiometry where the monomer emission increases as its excimer emission declines. By contrast, no significant spectral changes were observed upon addition of most of the other metal ions; however, when other heavy metal ions such as Pb^{2+}, Hg^{2+}, and Cu^{2+} were added to the solution of **8**, we unexpectedly observed a quenched fluorescence in both monomer and excimer emissions due to heavy metal ion effects. In contrast, **7** bearing only one pyrene unit, shows no significant spectral changes upon addition of any of the metal ions used apart from the heavy metal ions where quenching is again observed. The two triazole units of **8** are thus proven to form an efficient and selective metal ion binding site, whereas **7**, which features only one triazole binding site, is unable to form effective complexes despite the inclusion of an additional carbonyl binding site. Furthermore, the geometry of the binding site of the ligand, in which the two N atoms of triazole rings are arranged distally on the calix[4]arene scaffold, seems to be ideal in terms of arrangement and size for recognition of transition metal cations.[43]

Figure 4 shows the titration profiles of **8** on Cd^{2+} and Zn^{2+} addition. When the concentration of Cd^{2+} is increased up to

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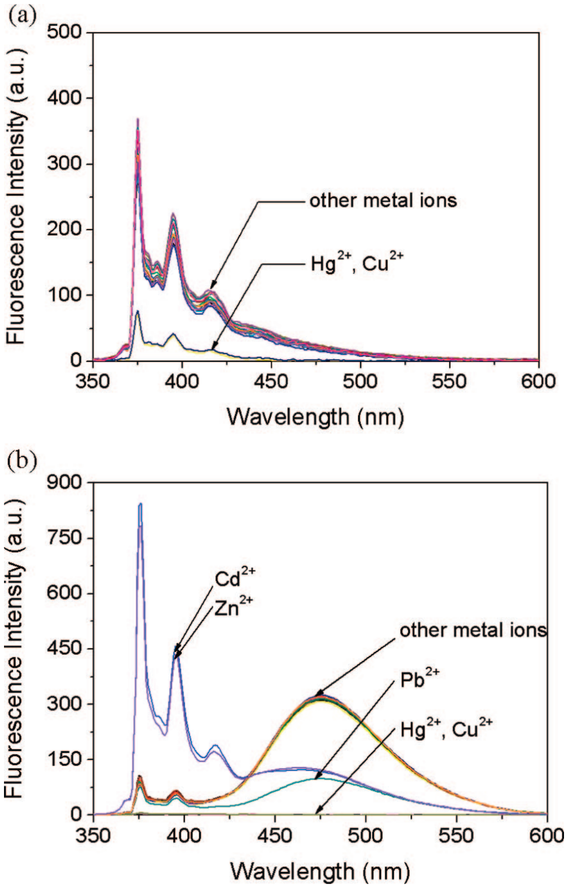

FIGURE 3. Fluorescence spectra of (a) **7** and (b) **8** (6.0 μM) upon addition of ClO_4^- salts of Li^+, Na^+, K^+, Rb^+, Cs^+, Mg^{2+}, Ca^{2+}, Sr^{2+}, Ba^{2+}, Ag^+, Cu^{2+}, Zn^{2+}, Cd^{2+}, Hg^{2+}, and Pb^{2+} (100 equiv) in CH_3CN.

1.2×10^{-4} M, the intensity is increased by 10-fold in monomer emission. The association constants (K_a)[49] of **8** were thus determined to be 5.18×10^4 and 1.7×10^4 M^{-1} for Cd^{2+} and Zn^{2+}, respectively. The quantum yields ($\Phi_f^{[d]}$)[50] of **8**, **8**-Cd^{2+}, and **8**-Zn^{2+}, referenced to anthracene, were also determined and found to be 0.229, 0.267, and 0.258, respectively.

To utilize **8** as an ion-selective fluorescence chemosensor for Cd^{2+} and Zn^{2+} the effect of competing metal ions was determined. Compound **8** (6.0 μM) was treated with 20 equiv of Cd^{2+} or Zn^{2+} in the presence of other metal ions (20 equiv). As shown in Figure 6, no interference in detection of Cd^{2+} and Zn^{2+} was observed in the presence of group 1 or group 2 metals or with silver and lead. However, the quenching effects of mercury and copper do abolish the ratiometric effect on binding of Cd^{2+} and Zn^{2+}. Thus it is notable that **8** can be used as a Cd^{2+} or Zn^{2+} selective ratiometric fluorescent sensor in the presence of most competing cations.

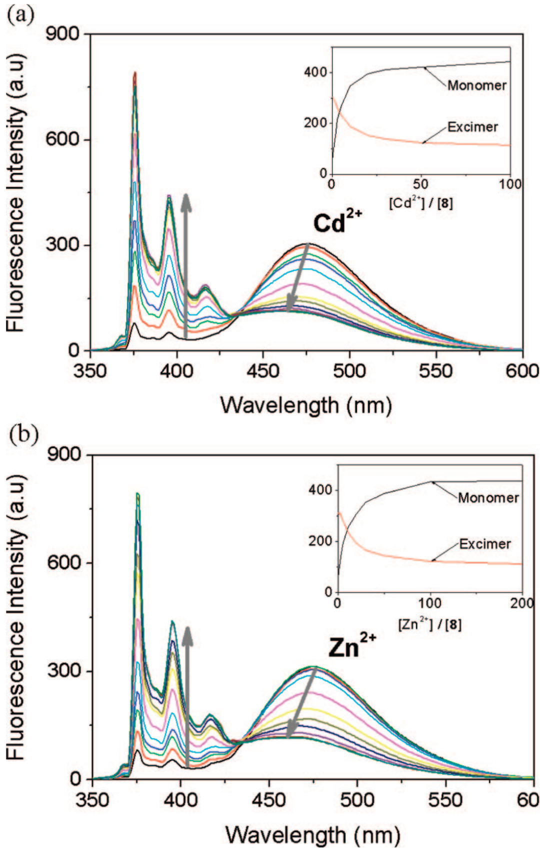

FIGURE 4. Fluorescence spectra of **8** (6.0 μM) in CH_3CN upon addition of increasing concentrations of (a) $Cd(ClO_4)_2$ and (b) $Zn(ClO_4)_2$ (0, 6, 12, 18, 30, 60, 120, 180, 300, 600, 1200, 1800, 3000 μM) with an excitation at 343 nm.

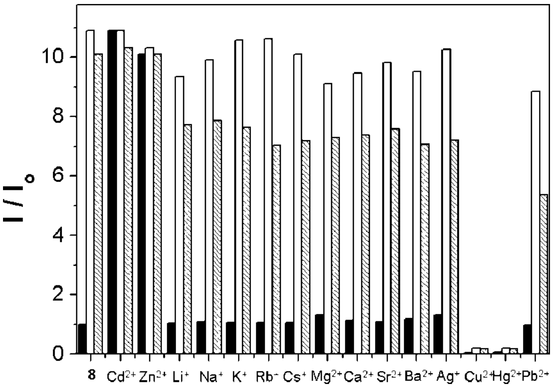

FIGURE 5. Fluorescence intensities after treatment of **8** in CH_3CN with a variety of metal perchlorates, and relative binding abilities of **8** to different metal ions compared to Cd^{2+} and Zn^{2+}, respectively. Black bar, 6.0 μM of **8** with 20 equiv of metal ion stated. White bar, 6.0 μM of **8** with 20 equiv of metal ion in 20 equiv of Cd^{2+} (for Cd^{2+} effect of 40 equiv Cd^{2+}). Slant line bar, 6.0 μM of **8** with 20 equiv of metal ion in 20 equiv of Zn^{2+} (for Zn^{2+} effect of 40 equiv Zn^{2+}) ($\lambda = 376$ nm). The responses of the sensor **8** to cadmium and zinc, in the absence of competing ions, are included as controls: black bar, no metal ion added; white bar, 6.0 μM of **8** with 20 equiv of Cd^{2+}; slant line bar, 6.0 μM of **8** with 20 equiv of Zn^{2+}.

^1H NMR spectroscopy of **8**, **8**-Cd^{2+}, and **8**-Zn^{2+} in CD_3CN was undertaken to determine the complexation mode of **8** for metal cations, which results in the excimer emission changes. The spectral differences are depicted in Figure 6. Some significant spectral changes are observed in the ^1H NMR spectra on addition of both of the cations. For example, upon interaction with Cd^{2+}, H_b (Figure 6) on the triazole ring undergoes a downfield shift by 0.26 ppm to 7.79 whereas the O*CH*$_2$-triazole linker proton H_c is shifted from 4.79 to 4.25 ppm. Similarly, in the presence of Zn^{2+}, the H_b peak is downfield shifted by 0.05 ppm and the H_c peak is upfield shifted by 0.19 ppm. These spectral changes suggest that both Cd^{2+} and Zn^{2+} are bound by the nitrogen atom of the triazole ring.[44] This putative binding

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(49) Association constants were calculated by using the computer program *ENZFITTER*, available from Elsevier-BIOSOFT, 68 Hills Road, Cambridge CB2 1LA, United Kingdom.

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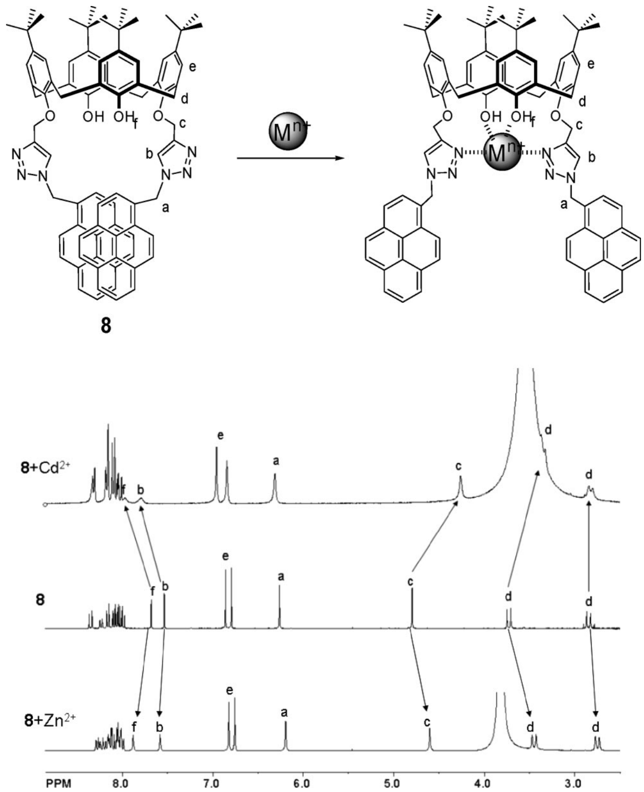

FIGURE 6. The proposed structure for **8** + metal ions, and ^{1}H NMR spectra of **8** in CD_3CN and in the presence of $Cd(ClO_4)_2$ and $Zn(ClO_4)_2$ in a 1:1 ratio (full spectra are available in the Supporting Information, Figures S17 and S18

mode is further elucidated by additional changes in the spectra which point to the metal being bound by the upper part of the triazole ring with the aid of two facing phenol groups. In particular, the phenol-H_f is downfield shifted by 0.29 and by 0.20 ppm with Cd^{2+} and Zn^{2+}, respectively, whereas the H_a peak proximal to the pyrene does not undergo a significant change in the presence of the metal cations. This binding mode is in line with the fluorescence changes observed as the induced conformational changes of the triazole units by 1:1 complexation would prevent the two pyrene molecules from maintaining the $\pi-\pi$ interaction necessary for excimer emission, but instead would force their separation and lead to the increasing monomer emission of **8**, which is observed. It is interesting to note that the extent of chemical shift changes is in agreement with the association constants ($Cd^{2+} > Zn^{2+}$) calculated from the fluorescence spectrometry results suggesting that Cd^{2+} is likely to interact with the triazole group of **8** more strongly than the Zn^{2+} cation.

The 1:1 binding mode proposed from the ^{1}H NMR studies is further confirmed by mass spectrometry in the presence of the metal cations. The FAB-MS spectra of mixtures of **8** with cadmium and zinc showed exclusively the formation of **8**$\cdot Cd^{2+}$ (*m/z* 1351.0 (calcd = 1352.54) [**8**$\cdot Cd^{2+}$-H^+]) and **8**$\cdot Zn^{2+}$ (1302.0 (calcd = 1302.57) (Supporting Information, Figures S15 and S16).

In summary, the synthesis of a new calix[4]arene fluorescent chemosensor **8** has been achieved in a short high yielding synthetic sequence from commercial starting materials. The inclusion of 1,2,3-triazoles as both spacers and cation-binding sites coupled with pyrene reporting units onto a rigid calyx[4]arene support provides a highly selective sensor for Cd^{2+} and Zn^{2+} ions. Binding of Cd^{2+} and Zn^{2+} ions occurs in a ratiometric manner through an enhanced monomer and declining excimer emission spectrum and can be additionally observed through changes in both the ^{1}H NMR and FAB-MS spectra. This work opens up the possibility of a family of highly selective sensors for a range of cations based on conformationally tuneable calixarene platforms, an area we are currently exploring.

Experimental Section

1-Bromomethylpyrene (2). Phosphorus tribromide (1.75 g, 6.45 mmol) was added to a suspension of commercial 1-pyrenemethanol (1) (1.00 g, 4.30 mmol) in 5 mL of dry THF and stirred at room temperature for 30 min. The resulting mixture was filtered and the residue was washed with Et_2O to yield the desired bromomethyl compound (**2**) as a yellow solid (1.04 g, 82%). Mp 145−146 °C. ^{1}H NMR (300 MHz) δ 8.31 (1H, d, J = 10 Hz), 8.15 (3H, m), 7.98 (4H, m), 5.18 (2H, s). ^{13}C NMR δ 32.46, 123.01, 124.79, 125.04, 125.28, 125.81, 125.83, 126.46, 127.52, 127.88, 128.21, 128.42, 129.24, 130.72, 130.03, 131.38, 132.12. IR υ 3037.359, 2987.080, 2883.720, 2119.843, 1915.830, 1789.935, 1587.225, 1556.438, 1514.198, 1310.830, 1244.134, 1200.661, 1183.767, 1083.749, 842.962, 838.874, 826.743 cm^{-1}. Electro Spray MS ($C_{17}H_{11}Br$ = 295.17) 159.455 [M − Br].

1-Azidomethylpyrene (3). Sodium azide (164 mg, 2.54 mmol) was added to a solution of bromomethylpyrene **2** (500 mg, 1.69 mmol) in 3 mL of anhydrous DMF and the suspension was heated at 60 °C for 6 h. The mixture was then cooled and diluted with water. The aqueous phase was extracted with Et_2O, the organic phase was dried (Na_2SO_4), and the solvent was evaporated to yield the azide (**3**) as a yellow waxy solid (395 mg, 91%). Mp 59−61 °C. ^{1}H NMR (300 MHz) δ 8.14 (4H, m), 7.95 (5H, m), 7.98 (4H, m), 4.95 (2H, s). ^{13}C NMR δ 53.12, 122.68, 124.66, 125.07, 125.56, 125.63, 126.19, 127.34, 127.46, 127.89, 128.29, 128.40, 129.27, 130.75, 131.24, 131.81. IR υ 3041, 2099, 2079, 1601, 1251, 1227, 1180 cm^{-1}. Electro Spray MS ($C_{17}H_{11}N_3$ = 257.29) 242.12 [M − N], 230.12 [M − 2N], 215.10 [M − 3N].

5,11,17,23-Tetra-*tert*-butyl-25,26,27-trihydroxy-28-propargylcalix[4]arene (4) and 5,11,17,23-Tetra-*tert*-butyl-25,27-dihydroxy-26,28-dipropargylcalix[4]arene (5). *p-tert*-Butylcalix[4]arene (3.10 g, 4.78 mmol) and K_2CO_3 (0.57 g, 4.12 mmol) were heated at reflux for 1 h in acetone (50 mL). Propargyl bromide (80% in toluene, 0.82 g, 6.89 mmol) was added and the mixture refluxed for 18 h. The solvents were evaporated and the residue partitioned between 10% HCl and CH_2Cl_2. The organic layer was separated and dried (Na_2SO_4) and the solvents were evaporated. The residue was purified by column chromatography on silica gel with 1:1 cyclohexane/CH_2Cl_2 as eluent to yield the title compound **4** (1.17 g, 36%) and additionally the dialkyne **5** (0.79 g, 23%). Analytical data of **4** and **5** were consistent with the materials prepared in the corresponding references.[47,48]

5,11,17,23-Tetra-*tert*-butyl-25,27-dihydroxy-26-methylacetate-28-propargylcalix[4]arene (6). **4** (1.00 g, 1.47 mmol) and K_2CO_3 (203 mg, 1.47 mmol) were heated at reflux in 30 mL of acetone for 1 h. $BrCH_2CO_2CH_3$ (225 mg, 1.47 mmol) was added and the mixture was refluxed for 18 h. The solvent was evaporated and the residue was partioned between 10% HCl and CH_2Cl_2. The organic layer was separated and dried (Na_2SO_4) and the solvents were evaporated. The residue was purified by column chromatography on silica gel with CH_2Cl_2 as eluent to yield **6** (915 mg, 33%) as a white solid. Mp 112−114 °C. ^{1}H NMR (300 MHz) δ 6.97 (4H, s), 6.68 (2H, s), 6.67 (2H, s), 6.62 (2H, s), 4.69 (2H, d, J = 2.3 Hz), 4.60 (2H, s), 4.32 (4H, d, J = 13.2 Hz), 3.77 (3H, s), 3.25 (4H, d, J = 13.2 Hz), 2.45 (1H, t, J = 2.3 Hz), 1,21 (18H, s), 0.85 (9H, s), 0.83 (9H, s). ^{13}C NMR (75 MHz) δ 30.96, 31.69, 32.09, 33.83, 33.87, 52.17, 63.15, 72.38, 96.13, 125.06, 125.57, 125.71, 127.94, 128.09, 132.15, 132.76, 141.58, 150.37, 169.44. MALDI-TOF MS (758.45) 759.455 [M + H]. Microanalysis Calcd: C, 79.12;

H, 8.23. Found: C, 78.87; H, 7.96. IR υ 3423, 2952, 1757, 1482, 1360, 1301, 1190, 1123 cm^{-1}.

5,11,17,23-Tetra-*tert*-butyl-25,27-dihydroxy-26-methylacetate-28-(1,2,3-triazol-1-methyl pyrene)calix[4]arene (7). Copper iodide (20 mg) was added to 5,11,17,23-Tetra-*tert*-butyl-25,27-dihydroxy-26-methylacetate-28-propargylcalix[4]arene (**6**) (320 mg, 0.42 mmol) and azide (**3**) (275 mg, 1.07 mmol) in anhydrous DMF (15 mL) and the mixture was heated at 90 °C for 2 h. The resulting solution was cooled and diluted with water. The mixture was filtered, the residue was washed with water and then taken up in CH_2Cl_2 and dried (Na_2SO_4). The desired compound **7** (236 mg, 56%) was isolated as a buff solid following column chromatography by eluting with 50:1 CH_2Cl_2/CH_3OH. Mp 225−227 °C. ^{1}H NMR (300 MHz) δ 8.00−8.50 (10H, m), 7.21 (2H, s), 7.05 (2H, d, J = 2.5 Hz), 7.00 (2H, d, J = 2.5 Hz), 6.77 (4H, d, J = 6.0 Hz), 6.47 (2H, s), 5.24 (2H, s), 4.51 (2H, s), 4.21 (2H, d, J = 12.3 Hz), 4.20 (2H, d, J = 14.1 Hz), 3.64 (3H, s), 3.23 (2H, d, J = 12.3 Hz), 3.22 (2H, d, J = 14.1 Hz), 1.30 (18H, s), 0.95 (9H, s), 0.94 (9H, s). ^{13}C NMR (75 MHz) δ 30.93, 31.60, 31.70, 33.81, 33.91, 51.91, 52.16, 70.25, 71.89, 122.19, 124.97, 125.08, 125.12, 125.25, 125.68, 125.75, 126.19, 127.13, 127.31, 127.52, 127.58, 127.99, 128.03, 128.75, 132.26, 132.65, 141.50, 149.32, 149.67, 150.45, 169.36. MALDI-TOF MS (1016.31) 1016.53 [M$^+$]. IR υ 3439, 2953, 2863, 1750, 1682, 1595, 1482, 1462, 1431, 1361, 1299, 1191, 1123 cm^{-1}.

5,11,17,23-Tetra-*tert*-butyl-25,27-dihydroxy-26,28-di(1,2,3-triazol-1-methylpyrene)calix[4]arene (8). Copper iodide (20 mg) was added to 5,11,17,23-tetra-*tert*-butyl-25,27-dihydroxy-26,28-dipropargylcalix[4]arene (**5**) (394 mg, 0.54 mmol) and azide **3** (350 mg, 1.36 mmol) in 15 mL of anhydrous DMF and the mixture was heated at 90 °C for 2 h. The resulting solution was cooled and diluted with water. The mixture was filtered, then the residue was washed with water and then taken up in CH_2Cl_2 and dried (Na_2SO_4). The residue eluted from a column chromatography of silica gel with 30:1 CH_2Cl_2/acetone to give the desired material **6** (388 mg, 57%) as a cream solid. Mp 198−200 °C. ^{1}H NMR (300 MHz) δ 7.62−8.09 (9H, m), 7.55 (2H, br s), 6.70 (4H, s), 6.61 (2H, s), 6.48 (4H, s), 6.00 (4H, s), 4.74 (4H, s), 3.61 (4H, d, J = 13 Hz), 2.82 (2H, d, J = 13 Hz), 1.15 (18H, s), 0.74 (18H, s). ^{13}C NMR (75 MHz) δ 30.84, 31.45, 31.67, 33.71, 33.78, 121.94, 124.39, 124.77, 124.87, 125.37, 125.73, 125.81, 126.21, 127.25, 127.33, 127.45, 128.14, 128.84, 130.50, 131.09, 131.92, 132. 43, 141.28, 147.04, 149.43, 149.98. MALDI-TOF MS (1238.64) 1239.60 [M + H]. IR υ 3369, 2950, 2361, 2091, 1687, 1481, 1461, 1390, 1364, 1245, 1169, 1120 cm^{-1}.

Fluorescence Studies. UV/vis and fluorescence spectra were recorded with a S-3100 spectrophotometer and a RF-5301PC spectrophotometer, respectively. Stock solutions (1.00 mM) of the metal perchlorate salts were prepared in CH_3CN. Stock solutions of **7** and **8** (0.06 mM) were prepared in CH_3CN. For all measurements of fluorescence spectra, excitation was at 343 nm with excitation and emission slit widths at 3.0 nm. UV/vis and fluorescence titration experiments were performed with 6.0 μM solutions of **7** and **8** in CH_3CN and varying concentrations of the metal perchlorate in CH_3CN.

X-ray Studies. X-ray data for **8** were collected on a Bruker SMART APEXII diffractometer equipped with graphite monochromated Mo Kα radiation (λ = 0.71073 Å). Preliminary orientation matrix and cell parameters were determined from three sets of ω scans at different starting angles. Data frames were obtained at scan intervals of 0.5° with an exposure time of 10 s per frame. The reflection data were corrected for Lorentz and polarization factors. Absorption corrections were carried out with SADABS.[51] The structures were solved by direct methods and refined by full-matrix least-squares analysis, using anisotropic thermal parameters for non-hydrogen atoms with the SHELXTL program.[52] The SQUEEZE routine of the PLATON program was employed to calculate the disorder area of the solvent molecule and get rid of its contribution to the whole intensity data. Hydrogen atoms were calculated at idealized positions and refined with the riding models.

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Supporting Information Available: General experimental methods, ^{1}H and ^{13}C NMR for **2**, **3**, and **6**−**8**, MS spectra for **6**−**8** and **8·Cd^{2+}** and **8·Zn^{2+}**, ORTEP diagram for **8**, and Cartesian coordinates for **8**. This material is available free of charge via the Internet at http://pubs.acs.org.

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