



## Dual-mode recognition of transition metal ions by bis-triazoles chained pyrenes

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### ABSTRACT

Fluorescent chemosensors **7–10**, with variable methylene chain length as spacers between the two triazole methyl ether units, have been synthesized under ‘Click’ condition, where the bistriazoles are used as the metal ion binding sites and the pyrenes as the fluorophores. Compound **10**, having the longest methylene chain among **7–10**, shows monomer and excimer fluorescence quenching in acetonitrile toward  $\text{Ni}^{2+}$ ,  $\text{Pb}^{2+}$ ,  $\text{Cu}^{2+}$ ,  $\text{Hg}^{2+}$ , and  $\text{Cr}^{3+}$  ions, however, it shows an enhanced monomer but a decreased excimer emission when complexed with  $\text{Cd}^{2+}$  and  $\text{Zn}^{2+}$  ions.

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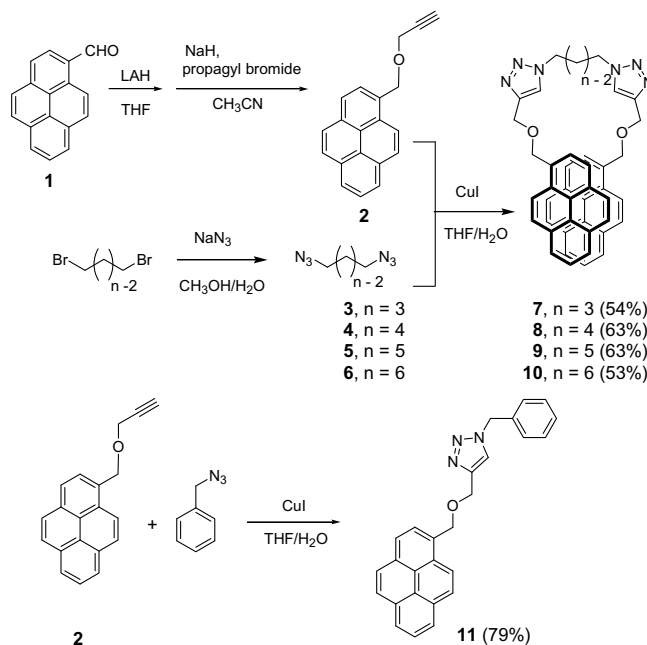
The development of selective chemosensors for the signaling of chemically and biologically important metal ions continues to draw much attention in the field of supramolecular chemistry.<sup>1</sup> An effective fluorescent chemosensor must convert the event of cation recognition by the ionophore into an easily monitored and highly sensitive light signal from the fluorophore. Pyrene is one of the most useful fluorogenic units because it emits not only from the monomer but also from the excimer, moreover, the ratio of its monomer to excimer emission is a sensitive probe for conformational change.<sup>2</sup> For example, it was reported that two pyrenyl moieties, connected by a series of polyoxy-ethylenes<sup>2b</sup> or dioxaoctanediamides,<sup>2c</sup> showed moderate to excellent selectivities toward  $\text{Ca}^{2+}$  and  $\text{Hg}^{2+}$  ions, respectively. It has also been shown that a pentyptecene system, bearing two end pyrenyl moieties connected by polyoxyethylenes, exhibited a novel blue shift along with an intensity enhancement of the pyrene excimer emission in the presence of  $\text{Cu}^{2+}$ .<sup>2d</sup> These reports prompted us to explore the possibility of combining two terminal pyrenes with bistriazoles for metal ion screening studies because the latter heterocycles are lately recognized as potential metal ion coordination ligands.<sup>3,4c</sup>

We have previously reported<sup>4</sup> the synthesis of a new fluorescent on–off switchable calix[4]crown using the ‘click chemistry’<sup>5</sup> of an azide and an alkyne to form a triazole metal ion binding site. Herein, we report the synthesis of 1,*n*-bispyrenyl-methoxymethyl-triazole-alkanes **7–10** and the study of their reversible conformational transformation in the presence of metal ions using the pyrene monomer/excimer emission as a probe.

The reaction of 1-(propargyloxymethyl)pyrene **2** with corresponding 1,*n*-bisazides (**3–6**) and benzylazide under click conditions afforded the target molecules **7–11** in 53–79% yields, where triazoles are designed to function as the metal ion binding sites and pyrenes are used as the reporting fluorophores.<sup>2,6–9</sup>

(Scheme 1). The formation of triazoles **7–11** was readily monitored by <sup>1</sup>H NMR by the appearance of a new singlet of triazole proton around  $\delta$  7.4 while the triplet acetylenic proton of compound **2** around  $\delta$  2.4 ( $J = 2.1$  Hz) disappeared.

The fluorescence spectra of **7–10** were then taken in MeCN which showed a strong intramolecular excimer emission around 482 nm and a weak monomer emission around 376 and 396 nm. The former emission band was attributed to the overlap of two



Scheme 1. Syntheses of chemosensors **7–11**.

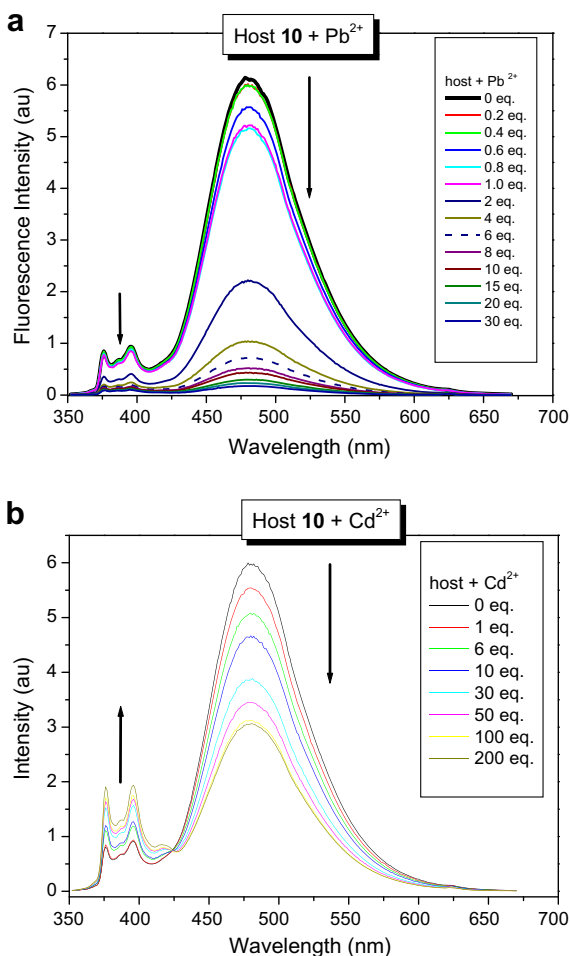
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pyrene units in an intramolecular  $\pi$ - $\pi$  stacking under UV irradiation.<sup>2</sup> The changes of fluorescence intensities of **7–10** (10  $\mu$ M) in the presence of 15 metal perchlorates (10 equiv) were studied and the results are summarized in Table S1. The fluorescence of compound **7** was found to be selectively quenched by the addition of  $\text{Cu}^{2+}$ ,  $\text{Hg}^{2+}$ , and  $\text{Cr}^{3+}$  ions. Such a selective quenching by the same group of metal ions ( $\text{Cu}^{2+}$ ,  $\text{Hg}^{2+}$ , and  $\text{Cr}^{3+}$ ) was also observed on the mono-triazole model compound **11**. The results suggest that metal ions may be complexed by both the triazole group(s) and the oxygen atom(s) of **7** and **11**, which then quenched the fluorescence intensity of the pyrenes. The quenching of monomer emission in **7** and **11** can be explained as a reverse PET as well as a heavy atom effect;<sup>8</sup> that is, the pyrene units behaved as a PET donor and the metal ion bound triazole groups behaved as an electron acceptor. The quenching of excimer emission resulted from the conformational change caused by the two outward-facing triazole groups that turned inward upon binding with metal ions. Job plot experiments were carried out for **7** which revealed a 1:1 complex with  $\text{Cu}^{2+}$ ,  $\text{Hg}^{2+}$ , and  $\text{Cr}^{3+}$ , respectively. The association constants for complexation of **7** with  $\text{Cu}^{2+}$ ,  $\text{Hg}^{2+}$ , and  $\text{Cr}^{3+}$  in MeCN, using Stern–Volmer equation at low guest concentration (0–1.0 equiv), were calculated to be  $1.2 \times 10^5$ ,  $1.6 \times 10^5$ , and  $2.1 \times 10^5 \text{ M}^{-1}$ , respectively. Similar fluorescence quenching by  $\text{Cu}^{2+}$ ,  $\text{Hg}^{2+}$ , and  $\text{Cr}^{3+}$  was also observed for compounds **8–10**, however, the emission of **9** was further quenched by  $\text{Pb}^{2+}$  and the emission of **10** was further quenched by  $\text{Pb}^{2+}$  and  $\text{Ni}^{2+}$  ions (see Table S1). The fluorescence of compound **10** toward the 15 metal ions

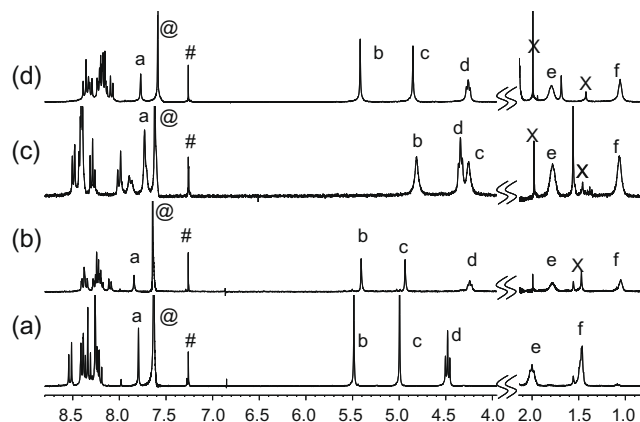
screened revealed two types of binding modes: (1) for  $\text{Cu}^{2+}$ ,  $\text{Hg}^{2+}$ ,  $\text{Cr}^{3+}$ ,  $\text{Pb}^{2+}$ , and  $\text{Ni}^{2+}$  ions, the monomer and excimer emissions were both quenched, and (2) for  $\text{Cd}^{2+}$  and  $\text{Zn}^{2+}$  ions, the monomer emission was enhanced but the excimer emission was quenched (see Figs. 1a and b). The association constants of **10** with  $\text{Pb}^{2+}$ ,  $\text{Ni}^{2+}$ ,  $\text{Cd}^{2+}$ , and  $\text{Zn}^{2+}$  ions in MeCN using Stern–Volmer plots were determined to be  $1.2 \times 10^5$ ,  $5.1 \times 10^3$ ,  $3.2 \times 10^3$ , and  $2.9 \times 10^3 \text{ M}^{-1}$ , respectively.

In order to gain insights into the complexation modes of these receptors with metal ions, we compared the  $^1\text{H}$  NMR spectra of **10** (5 mM) in the absence and presence of various metal cations in  $\text{CDCl}_3/\text{CD}_3\text{CN} = 3/1$  at 25  $^\circ\text{C}$  (see Figs. 2a–d). The  $^1\text{H}$  NMR spectra of **10** with  $\text{Cu}^{2+}$ ,  $\text{Cr}^{3+}$ , and  $\text{Ni}^{2+}$  were broadened due to the high spin states of these metal ions, therefore, they were not analyzed. In the titration of **10** with  $\text{Hg}^{2+}$ , precipitate was observed which decreased the  $^1\text{H}$  NMR signals substantially. Nevertheless, the methine protons  $\text{H}_a$  of triazoles disappeared in the presence of  $\text{Hg}^{2+}$  and the methylene protons ( $\text{H}_b$ ,  $\text{H}_c$ ,  $\text{H}_d$ ,  $\text{H}_e$ , and  $\text{H}_f$ ) exhibited substantial up-field shifts ( $\Delta\delta = -0.20$ ,  $-0.43$ ,  $-0.57$ ,  $-0.33$ , and  $-0.47$  ppm) upon complexation with 1 equiv of  $\text{Hg}^{2+}$ . The complexation of **10** with  $\text{Hg}^{2+}$  is expected to reduce the electron density of the coordination sites and induce a down-field shift of the nearby proton signals; however, up-field shift was observed for all the methylene protons. Thus, we believe that there must be a change of conformation which causes the methylene protons to be shielded by the pyrene rings. A similar change in proton chemical shifts of **10** was observed when it was titrated with  $\text{Pb}^{2+}$  ion. In the complexation of **10** with  $\text{Cd}^{2+}$ , the signals of  $\text{H}_b$  and  $\text{H}_c$  were slightly up-field shifted by 0.02 and 0.11 ppm, however, the signals of  $\text{H}_d$ ,  $\text{H}_e$ , and  $\text{H}_f$  were more up-field shifted by 0.17, 0.14, and 0.36 ppm, respectively. The fact that the chemical shift of  $\text{H}_b$  of compound **10** was more affected by  $\text{Pb}^{2+}$  than by  $\text{Cd}^{2+}$  implies that **10** complexed with these two metal ions in a different mode (vide infra). On the one hand, compounds **7–9** did not show any fluorescence change upon adding  $\text{Cd}^{2+}$  or  $\text{Zn}^{2+}$  probably because their bis-triazoles could not find a proper conformation to accommodate either one of them. On the other hand, compound **10** did form complexes with  $\text{Cd}^{2+}$  and  $\text{Zn}^{2+}$  because the cavity formed by the methylene chains and the two triazoles was just big enough to accommodate them.

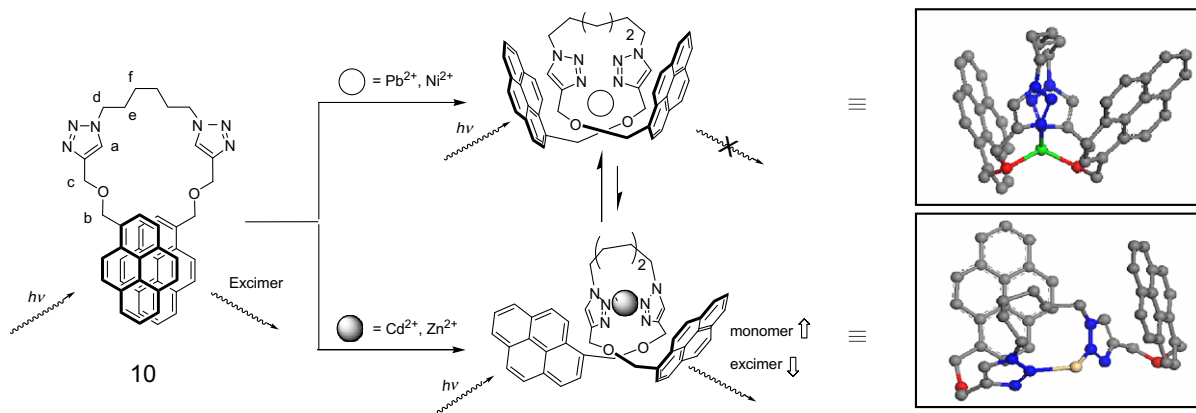
Based on the titration results of  $^1\text{H}$  NMR and fluorescence spectrometry on **10**, we proposed that **10** shows a dual-mode recognition toward transition metal ions (see Scheme 2): (a)  $\text{Ni}^{2+}$  and  $\text{Pb}^{2+}$  were bound between the oxygen atoms of the ether groups and the triazoles 3'-N which distorted the original conformation and



**Figure 1.** Changes in fluorescence spectra ( $\lambda_{\text{ex}} = 312 \text{ nm}$ ) of **10** (10  $\mu$ M) in MeCN solution at 298 K with the addition of (a)  $\text{Pb}^{2+}$ , and (b)  $\text{Cd}^{2+}$  ions.



**Figure 2.**  $^1\text{H}$  NMR of **10** (5 mM) in  $\text{CDCl}_3/\text{CD}_3\text{CN} = 3/1$  (a) and in the presence of 5 mM of various metal ions (b)  $\text{Hg}^{2+}$ , (c)  $\text{Pb}^{2+}$ , and (d)  $\text{Cd}^{2+}$ . Where @ denotes internal  $\text{CHCl}_3$ , # denotes external  $\text{CHCl}_3$ , and X denotes impurity upon addition of metal ion.



**Scheme 2.** Possible bonding modes of **10** with various metal ions, where red atom stands for oxygen, blue atom stands for nitrogen, green atom stands for  $\text{Pb}^{2+}$  ion, and light yellow atom stands for  $\text{Cd}^{2+}$  ion.

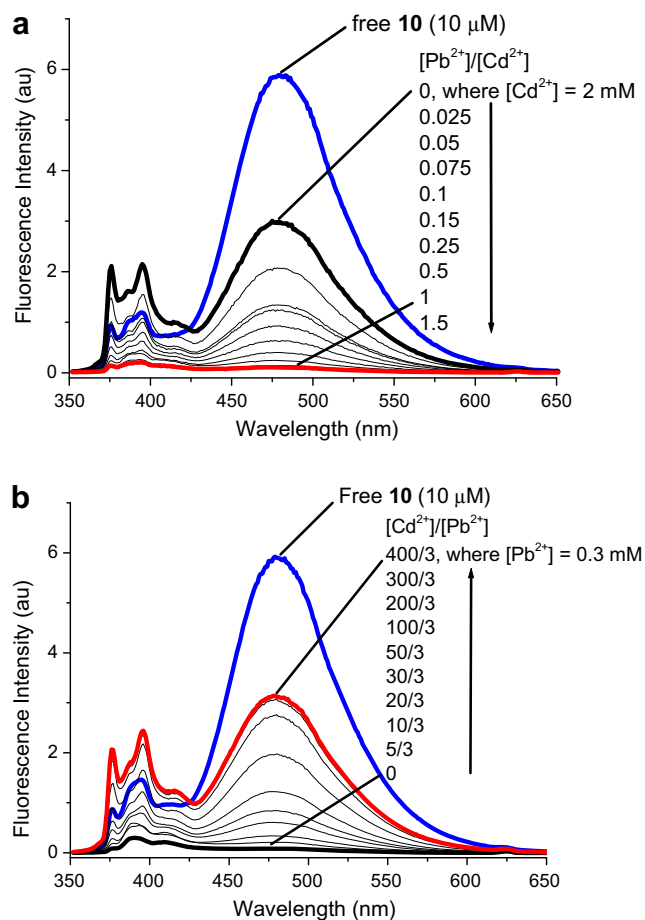
quenched the monomer and excimer emission; (b)  $\text{Cd}^{2+}$  and  $\text{Zn}^{2+}$  were bound with **10** by the two triazoles which not only enhanced the monomer emission but also quenched the excimer emission due to the separation of the two pyrene rings.

With regard to cation exchange of **10** with  $\text{Cd}^{2+}$  and  $\text{Pb}^{2+}$  ions, we observed an interesting on–off switching process.<sup>10</sup> When  $\text{Pb}^{2+}$  was titrated into a solution of preformed complex of **10**: $\text{Cd}^{2+}$  ( $\text{10}:\text{Cd}^{2+} = 1:200$ ), both the excimer and monomer emission bands

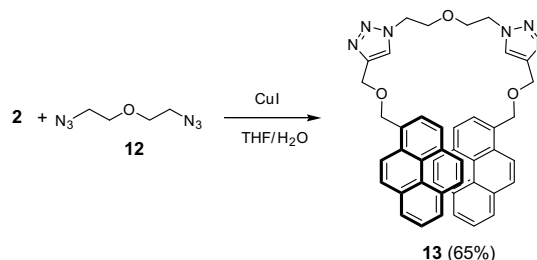
gradually quenched and became saturated after adding about same equiv of  $\text{Pb}^{2+}$  (vs  $\text{Cd}^{2+}$ ), (see Fig. 3a). In the reverse of this metal ion exchange process,  $\text{Cd}^{2+}$  was titrated into a preformed complex of **10**: $\text{Pb}^{2+}$  ( $\text{10}:\text{Pb}^{2+} = 1:30$ ), producing the fluorescence changes, shown in Figure 3b. In the former case, only 1 equiv of  $\text{Pb}^{2+}$  (vs  $\text{Cd}^{2+}$ ) was needed to fully substitute the  $\text{Cd}^{2+}$ , whereas in the latter case, about 130 equiv of  $\text{Cd}^{2+}$  (vs  $\text{Pb}^{2+}$ ) was needed to liberate  $\text{Pb}^{2+}$  ion from the **10**: $\text{Pb}^{2+}$  complex. The results confirm that **10** forms a stronger complex with  $\text{Pb}^{2+}$  than  $\text{Cd}^{2+}$ ; furthermore, it also shows that metal ion exchange is possible through the electrostatic repulsion between the two metal ions in two different binding sites. Thus, when a metal ion is bound by **10**, which contains two different recognition sites, it chooses the more favorable binding site.

If the proposed binding modes of **10** toward  $\text{Cd}^{2+}$  and  $\text{Zn}^{2+}$  are correct, we predicted that a new receptor **13**, where an oxygen atom replacing the middle carbon of the methylene spacer of **9**, should enhance its binding affinity toward the two metal ions (Scheme 3). Note that receptor **9** did not show any change in its monomer and excimer emission upon adding excess  $\text{Cd}^{2+}$  or  $\text{Zn}^{2+}$ ; however, receptor **13** showed an increase of monomer emission and a decrease of excimer emission upon adding  $\text{Cd}^{2+}$  or  $\text{Zn}^{2+}$ . Similar to receptor **10**, receptor **13** also showed significant fluorescence quenching toward  $\text{Cu}^{2+}$ ,  $\text{Hg}^{2+}$ ,  $\text{Cr}^{3+}$ , and  $\text{Pb}^{2+}$  (Fig. 4). The results support that the binding mode of receptor **13** toward  $\text{Cd}^{2+}$  and  $\text{Zn}^{2+}$  is similar to that of receptor **10** (Scheme 2) and is therefore enhanced by the addition of an ether linkage in the middle of the methylene chain of receptor **9**.

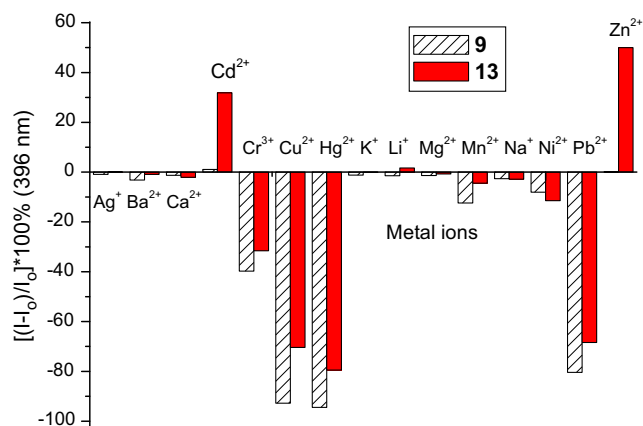
In conclusion, we have synthesized a series of new fluoroionophores **7–10** with pyrenylmethyl-oxy-methyl-bis-triazoles as the cationic binding sites. The series of receptors, like their control compound **11**, all showed strong fluorescence quenching toward  $\text{Cu}^{2+}$ ,  $\text{Hg}^{2+}$ , and  $\text{Cr}^{3+}$ , implying that they do not need two triazoles for the complexation of these ions. As the methylene chain length increases, the receptors **9** and **10** further responded to  $\text{Ni}^{2+}$ ,  $\text{Pb}^{2+}$ ,



**Figure 3.** Fluorescence emission changes for (a) **10**: $\text{Cd}^{2+}$  complex ( $\text{10}:\text{Cd}^{2+} = 1:200$ ) in MeCN upon adding various amounts of  $\text{Pb}^{2+}$  and (b) **10**: $\text{Pb}^{2+}$  complex ( $\text{10}:\text{Pb}^{2+} = 1:30$ ) in MeCN upon adding various amounts of  $\text{Cd}^{2+}$  (The excitation wavelength was 312 nm).



**Scheme 3.** Synthesis of chemosensor **13**.



**Figure 4.** Fluorescence intensity changes ( $(I - I_0)/I_0 \times 100\%$ ) of fluoroionophores **9** and **13** (each of  $10 \mu\text{M}$ ) in MeCN at 298 K upon addition of various metal perchlorates (10 equiv). Excitation wavelength was at 312 nm.

$\text{Cd}^{2+}$ , and  $\text{Zn}^{2+}$ . Two types of binding models were proposed for fluoroionophore **10** based on  $^1\text{H}$  NMR titration and fluorescence quenching studies (see Scheme 2). Thus, through the systematic variation of the chain length of these readily synthesized bistriazole-oxy-methylpyrenes, we found that fluoroionophores **7–10** and **13** are excellent chemosensors for heavy metal ions and they provide us valuable information about the conformational changes and ligation behavior toward various metal ions.

#### Acknowledgments

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#### Supplementary data

Experimental procedures,  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectral data of compounds **7–11** and **13**, and fluorescence and  $^1\text{H}$  NMR titration spectra of **10** with various metal perchlorates are available. Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tetlet.2008.10.147.

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