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Tetrahedron Letters 48 (2007) 2481–2484

Tetrahedron Letters

Fluorescent studies of two new binaphthyl–azacrown–anthracene fluorophores with metal ions and chiral guests: dual fluorescent detection via binaphthyl and anthracene groups

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Received 15 January 2007; revised 6 February 2007; accepted 8 February 2007
Available online 13 February 2007

Abstract—Two new binaphthyl–azacrown–anthracene fluorophores were synthesized. These new fluorescent receptors exhibited large fluorescent changes with aqueous Hg^{2+}, Cu^{2+} and Zn^{2+}. Interestingly, the fluorescent emissions from the binaphthyl and anthracene groups using different excitation wavelengths showed different patterns in the presence of metal ions. The chiral recognitions of these receptors with chiral ammonium guests were also examined.

Fluorescent chemosensors are particularly attractive on account of their simplicity and high detection limit. Furthermore, the detection of metal ions with a high specificity under physiologically relevant conditions is an important issue in the design of fluorescent chemosensors in biological and environmental applications.[1] In particular, mercury contamination occurs through oceanic and volcanic emission,[2] gold mining,[3] solid waste incineration, etc. The high toxicity of mercury has attracted considerable attention to the development of new fluorescent chemosensors[4] for the detection of mercury and mercuric salts.

Since Cram et al.[5] reported their pioneering studies on the use of chiral macrocyclic ligands in enantiomeric recognition, a large number of chiral macrocycles have been synthesized and examined.[6] However, to the best of our knowledge, the dual emissions from a binaphthyl group and another fluorophore, such as anthracene, have not been used to detect metal ions. The binaphthyl–azacrown–anthracene derivatives synthesized in this study showed different emission changes with metal ions when wavelengths of 290 nm and 336 nm (or 390 nm) were used to excite the binaphthyl or anthracene groups, which means that the fluorescent quenching and enhancing effects of metal ions on binaphthyl and anthracene groups are different.

We report the synthesis and binding properties of two new binaphthyl–azacrown–anthracene fluorophores as selective fluorescent chemosensors for Hg^{2+} in an aqueous solution, even though these receptors displayed moderate fluorescent enhancements with Zn^{2+} and Cu^{2+}. In addition, different emission patterns of these complexes were observed when different excitation wavelengths were used. These receptors also exhibited moderate selectivity for (*R*)-2-phenylglycinol over (*S*)-isomer.

The synthesis began with (*R*)-**3**, which was synthesized from (*R*)-(+)-1,1′-bi-2-naphthol according to the reported procedure.[7] (*R*)-**4** was synthesized using (*R*)-**3** and *p*-toluenesulfonamide in 59% yield after column chromatography using ethyl acetate–hexane as the eluent (1:4, v/v) (Scheme 1). The treatment of (*R*)-**4** with $LiAlH_4$ gave (*R*)-**5** in 89% yield. (*R*)-**5** was then reacted with either 9-bromomethylanthracene or 9-(10-bromomethyl) cyanoanthracene[8] to give (*R*)-**1** or (*R*)-**2** in 90% and 91% yield, respectively. The details of synthesis

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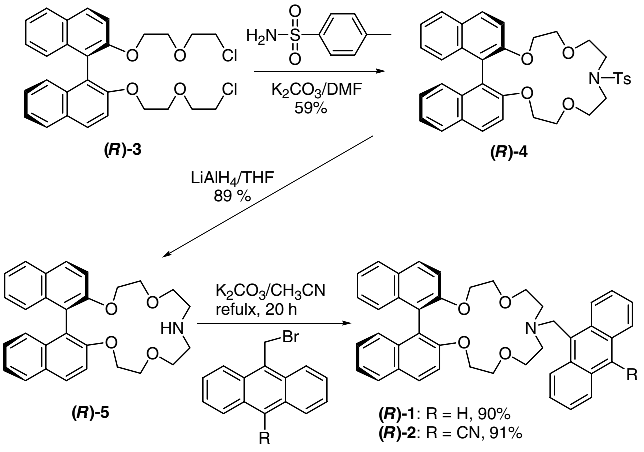
0040-4039/$ - see front matter © 2007 Published by Elsevier Ltd.
doi:10.1016/j.tetlet.2007.02.028



Scheme 1. Synthesis of compounds (*R*)-**1** and (*R*)-**2**.

and characterization data for new compounds are illustrated in the Supplementary data.

Ag^{+}, Ca^{2+}, Co^{2+}, Cu^{2+}, Cs^{+}, Hg^{2+}, K^{+}, Li^{+}, Mg^{2+}, Mn^{2+}, Na^{+}, Ni^{2+} and Zn^{2+} ions were used to evaluate the metal ion binding properties of compound **1**. All titration studies were carried out in CH_3CN–0.01 M HEPES (pH 7.4) (4:1, v/v) using a 10 µM of compound **1** or **2**. Using these metal ions (100 equiv), compound **1** displayed large CHEQ effects with Hg^{2+}, Zn^{2+} and Cu^{2+} (Fig. 1) with the maximum emission observed at 420 nm. The fluorescence spectra were obtained by exciting the anthracene fluorophore at 336 nm. Compound **2** showed a large CHEF effect with Hg^{2+}, even though there were relatively smaller CHEF effects with Cu^{2+} and Zn^{2+} (Fig. 2). In the case of compound **2**, 390 nm was used for to excite the fluorescent emission changes in compound **1** upon the addition of Hg^{2+} ions (Fig. 3). There was an almost 10-fold overall change in the emission of compound **1** upon the addition of Hg^{2+}. From the fluorescent titrations of compound **1**, the association constants for Hg^{2+} (Fig. 3), Zn^{2+} (S-Fig. 1) and Cu^{2+} (S-Fig. 2) were calculated to be 6400, 1240 and 2700 M^{-1} (errors <10%), respectively.[9] Large chemical shift changes of the benzylic protons as well as azacrown protons in **1** upon the addition of Hg^{2+} were observed in the ^{1}H NMR spectra (S-Fig. 3). In the presence of other metal ions (100 µM), only Cu^{2+} and Zn^{2+} displayed a small decrease in the emission spectra (<10%) of **1** (10 µM) with Hg^{2+} (50 µM). The association constants of compound **2** with Hg^{2+} (S-Fig. 4) and Cu^{2+} (S-Fig. 5) were calculated to be 5300 and 970 M^{-1} (errors <10%), respectively.[9]

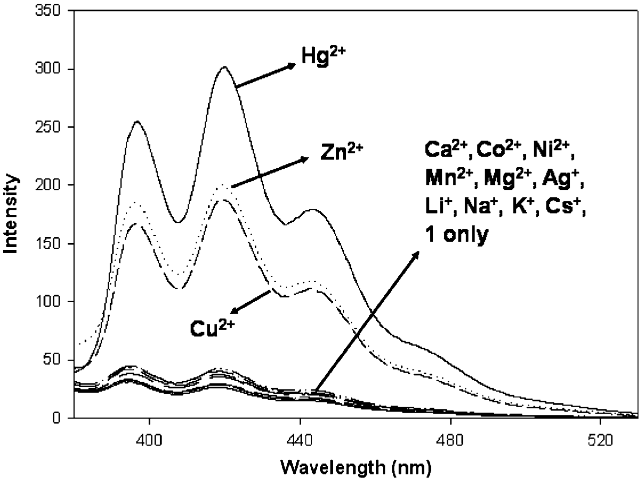


Figure 1. Fluorescent emission changes of **1** (10 µM) upon addition of various metal ions (100 equiv) in CH_3CN–0.01 M HEPES (pH 7.4) (4:1, v/v) (excitation at 336 nm).

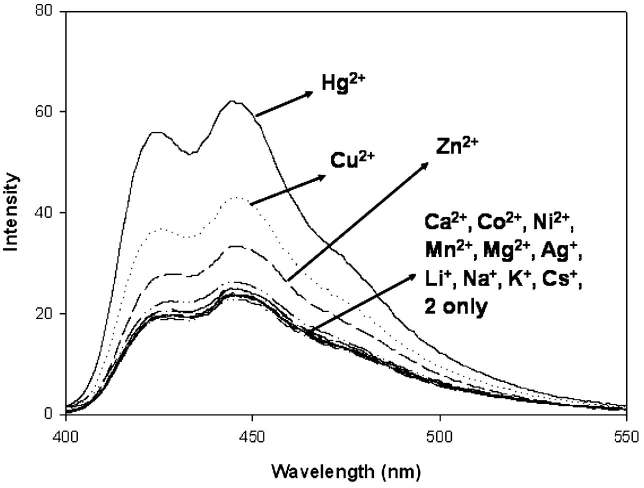


Figure 2. Fluorescent emission changes of **2** (10 µM) upon addition of various metal ions (100 equiv) in CH_3CN–0.01 M HEPES (pH 7.4) (4:1, v/v) (excitation at 390 nm).

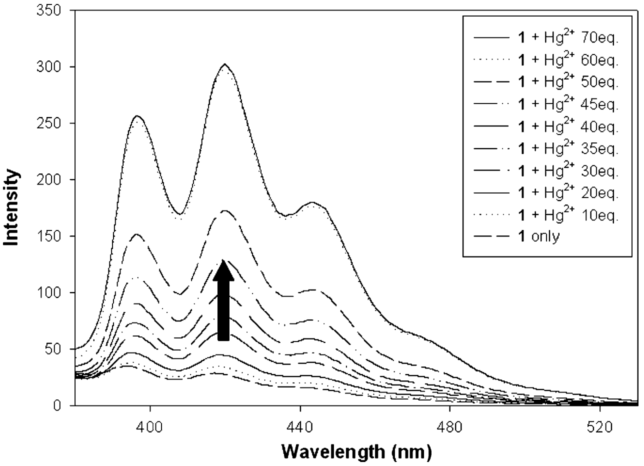


Figure 3. Fluorescent titrations of **1** (10 µM) with Hg^{2+} in CH_3CN–0.01 M HEPES (pH 7.4) (4:1, v/v) (excitation at 336 nm).

In the absence of protonation or metal ion chelation, non-bonded electrons of the intramolecular amine are available to undergo photo-induced electron transfer (PET) to the anthracene π-system, which efficiently quenches fluorescence.[10] Correspondingly, a low pH or the presence of non-quenching metal ions interrupts the PET mechanism and the anthracene fluorescence is restored. The binding of an amine group with metal ions in fluorophore-amine conjugates resulting in the elimination of photo-induced electron transfer (PET).[10]

Therefore, CHEF (chelation-enhanced fluorescence) is expected to be observed in these systems.

However, when compounds **1** and **2** were excited at 290 nm, the emission patterns were quite different from those excited at either 336 nm or 390 nm. As shown in Figure 4, unique dual emissions were observed upon the addition of Hg^{2+}, Zn^{2+} and Cu^{2+}. The addition of other metal ions, such as Ag^{+}, Ca^{2+}, Co^{2+}, Cs^{+}, K^{+}, Li^{+}, Mg^{2+}, Mn^{2+}, Na^{+} and Ni^{2+}, showed similar spectra to that of compound **1**. The emission at 355 nm can be attributed to the fluorescence of the binaphthyl group, and the emission at 420 nm is induced from anthracene. Unlike the emission spectra that were excited at 336 nm (Fig. 1), the binaphthyl group (emission at 355 nm) exhibited a CHEF effect with Zn^{2+} as well as a CHEQ (chelation-enhanced fluorescence quenching) effect with Cu^{2+} (Fig. 4). On the other hand, the addition of Hg^{2+} did not induce a significant change. For the second emission at 420 nm, there were large CHEF effects with Hg^{2+} and Zn^{2+}, and a relatively small CHEF effect with Cu^{2+}. The fluorescent enhancement at 355 nm with Zn^{2+} can be attributed to the blocking of a PET mechanism (from the phenolic oxygen atoms to the binaphthyl group) as explained above. On the other hand, a quenching metal ion, such as Cu^{2+} (via energy or electron transfer,[11] binds tightly to the ligand, and a CHEQ effect can be observed. As shown in Figure 5, compound **2** also showed similar emission changes at 355 nm. The fluorescent titration spectra of compound **2** (excitation at 290 nm) with Cu^{2+} displayed consistent quenching effects even though there were small CHEF effects up to 10 equiv of Cu^{2+} (S-Fig. 6).

The dual emissions of binaphthyl and anthracene groups can give more precise information regarding the fluorescent changes in the different metal ions, as shown in Figures 4 and 5. Furthermore, the binding selectivity of compounds **1** and **2** can be easily confirmed from the combination of Figures 1 and 4 or Figures 2 and 5.

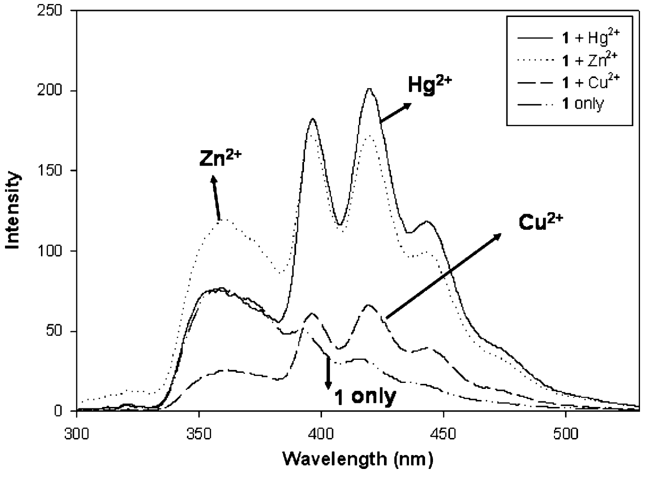


Figure 4. Fluorescent emission changes of **1** (10 μM) upon addition of Hg^{2+}, Zn^{2+} and Cu^{2+} (100 equiv) in CH$_3$CN–0.01 M HEPES (pH 7.4) (4:1, v/v) (excitation at 290 nm).

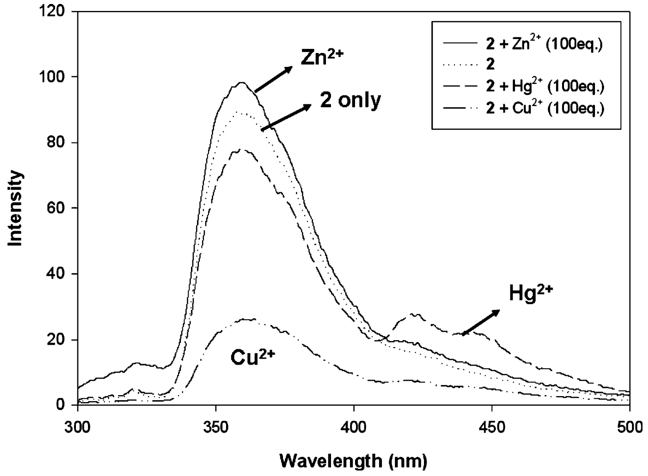


Figure 5. Fluorescent emission changes of **2** (10 μM) upon addition of Hg^{2+}, Zn^{2+} and Cu^{2+} (100 equiv) in CH$_3$CN–0.01 M HEPES (pH 7.4) (4:1, v/v) (excitation at 290 nm).

The chiral recognition of compound **1** was examined using hydrogenperchlorate salts of (*R*)-2-phenylglycinol and (*S*)-isomer in acetonitrile. From the fluorescent titrations of compound **1**, the association constants for the hydrogenperchlorate salts of (*R*)-2-phenylglycinol (Fig. 6) and (*S*)-2-phenylglycinol (S-Fig. 7) were calculated to be 45,000 and 34,500 M^{-1} (errors <10%), respectively.[9] The ammonium groups bound in the azacrown ring can prevent the PET mechanism from the benzylic nitrogen to anthracene group, which can induce CHEF effects. The moderate selectivity (1.3 times) for the hydrogenperchlorate salt of (*R*)-2-phenylglycinol over the (*S*)-isomer was observed. The ^{1}H NMR experiments (S-Figs. 8 and 9) showed that upon the addition of 5 equiv of the chiral guests in CD$_3$CN, there was a clear downfield shift of H-10 on anthracene (8.48–8.72 ppm for (*R*)-isomer; 8.48–8.69 ppm for (*S*)-isomer) as well as the benzylic CH$_2$ (4.36–5.20 ppm for (*R*)-isomer; 4.36–5.13 ppm for (*S*)-isomer), which shows that the benzylic nitrogen participates in the binding with

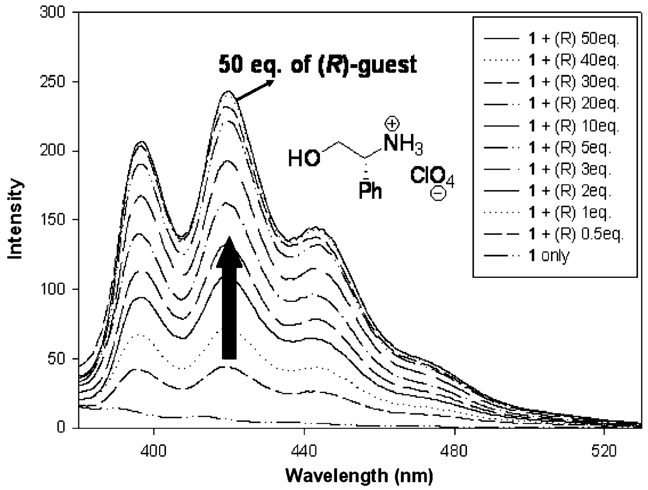


Figure 6. Fluorescent titrations of **1** (10 μM) with hydrogenperchlorate salt of (*R*)-2-phenylglycinol in CH$_3$CN (excitation at 336 nm).

the ammonium group of the guest. The NMR data also supports the moderate selectivity of the (*R*)-isomer, as shown in fluorescent study.

In conclusion, two new binaphthyl–azacrown–anthracene fluorophores were synthesized as selective fluorescent chemosensors for Hg^{2+} in aqueous solution, even though these receptors exhibited moderate fluorescent enhancements with Zn^{2+} and Cu^{2+}. Interestingly, the fluorescent emissions from the binaphthyl and anthracene groups using different excitation wavelengths showed different patterns in the presence of metal ions. All three metal ions, such as Hg^{2+}, Zn^{2+} and Cu^{2+}, showed CHEF effects when either 336 nm or 390 nm were used as the excitation wavelength. On the other hand, Zn^{2+} induced CHEF effects and Cu^{2+} induced large CHEQ effects when these compounds were excited at 290 nm. The different CHEF and CHEQ effects in the dual emission changes from a binaphthyl group and a second fluorophore can provide more precise detections of various analytes. These receptors also exhibited moderate selectivity (1.3 times) for the hydrogenperchlorate salt of (*R*)-2-phenylglycinol over the (*S*)-isomer.

Acknowledgements

This work was supported by a Grant from KOSEF (NRL program: M1-0318-00-0005), the Basic Science Research of KOSEF (R01-2006-000-10001-0) and BK21.

Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tetlet.2007.02.028.

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