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ORIGINAL ARTICLE

A novel switch-on fluorescent receptor for bromide based on an amide group

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Abstract A novel switch-on fluorescent receptor for bromide was demonstrated and its binding ability toward anions was investigated by fluorescence spectroscopes and ^{1}H NMR titration experiments. Addition of Br^- to a DMSO solution of *N*,*N*-di-*p*-bromophenyl-1,10-phenanthroline-2,9-diamide (1) resulted in an enhancement in fluorescence intensity at 377 nm and 396 nm. Two signaling transduction mechanisms were exploited to rationalize quenching and enhancement of the fluorescence emission: inhibition of a photo-induced electronic transfer mechanism (PET) and anion-induced increase of the rigidity of the host molecule.

Keywords Anion receptor · Fluorescence · Switch-on · Bromide · Amide

Introduction

The development of highly sensitive and selective detection techniques for the discrimination of relevant biologically active and toxic molecules is of considerable importance in the fields of chemical, biological, and environmental sciences [1, 2]. More specifically, biologically important inorganic anions such as fluoride, acetate, phosphate are associated with a wide range of biological functions [3, 4]. For example, phosphate is involved in a number of important biomineralization processes such as bone formation as well as pathological processes such as the genesis of renal stones [5] and the carboxylate anions exhibit specific biochemical behaviors in the enzymes and antibodies and are also critical components of numerous metabolic processes [6]. In particular, bromide could be found widely in nature such as salt well and saline and urine, serum and saliva of organism. However, bromide is one of the most difficult anions to be sensed due to the large ionic radius, low charge density and low hydrogen bonding ability. Consequently, the binding of Br^- ions within synthetic receptors remains as challenging today as it was when the first host species were introduced some 40 years ago [7, 8].

In general, the anion binding event can be transduced into observable signals: redox potential changes, UV-vis spectral changes, fluorescence emission changes and so on [9]. Of particular interest on this regard are fluorescence methods which will provide many advantages such as high sensitivity, convenience, rapid on-site evaluation and low cost. Although plenty of effective fluorescent sensors have been successfully developed for sensing anions, most of them exhibit fluorescence quenching (switch-off) [10–12], which is disadvantageous for a high signal output, and not fluorescence enhancement (switch-on), which is advantageous in terms of the detection limit and sensitivity, when bond to anions. Therefore, much attention has been attracted on the construction of a turn-on fluorescent sensor that is selective and sensitive to specific analyte [13, 14].

Commonly, a typical fluorescent anion sensor consists of a fluorophore and a binding unit [15]. In this paper, with the objective of showing turn-on fluorescent receptors, a novel anion sensors were designed and synthesized by introducing amide moieties (binding sites) into 1,10-

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phenanthroline group (fluorophore). Just as expected, the receptor 1 showed fluorescence enhancement upon interacting with anions though hydrogen bonding. And what is more, the receptor 1 exhibited the preference for bromide.

Experimental

Apparatus

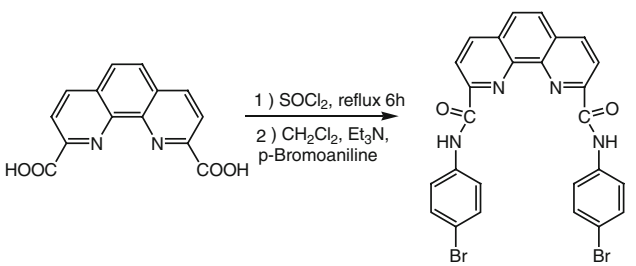
^{1}H NMR spectra were obtained on a Varian UNITY Plus-400 MHz Spectrometer. ESI-MS was performed with a MARINER apparatus. C, H, N elemental analyses were made on an elementar vario EL. Fluorescent spectra were recorded on a Shimadzu RF-5301PC Spectrophotometer at 298.2 ± 0.1 K and the width of the slits used is 5.

Chemicals

All reagents for synthesis obtained commercially were used without further purification. In the titration experiments, all the anions were added in the form of tetrabutylammonium (TBA) salts, which were purchased from Sigma-Aldrich Chemical, stored in a vacuum desiccator containing self-indicating silica and dried fully before using. DMSO was dried with CaH_2 and then distilled in reduced pressure.

Synthesis of *N*,*N*′-di-*p*-bromophenyl-1,10-phenanthroline-2,9-diamide (1)

The synthesis route of the receptor 1 was demonstrated in Scheme 1. To 1.1 g (4 mmol) 1,10-phenanthroline-2,9-dicarboxylic acid was added freshly distilled thionyl chloride (25 mL) and the mixture solution was refluxed for 6 h. Then, the solution was concentrated to under reduced pressure. The slight yellow residue was dissolved in 25 mL dry CH_2Cl_2 followed by addition of a catalytic amount of triethylamine. *p*-Bromoaniline (1.4 g, 8.1 mmol) were added slowly to the above-mentioned cold mixture solution, stirred for 3 days at room temperature, poured into saturated sodium bicarbonate solution, filtered and washed with water to give 1.0 g pure yellow solid after crystallization from DMF. Yield ≈42.1%. ^{1}H NMR (DMSO-d_6):δ11.48 (s, 2H, NH), 8.87 (d, J = 8.4 Hz, 2H, phen-H), 8.62 (d, J = 8.4 Hz, 2H, phen-H), 8.28 (m, 2H, phen-H), 8.15(d, J = 8.4 Hz, 2H, phen-H), 7.73 (d, J = 8.0 Hz, phen-H); ESI-mass: *m/z* 576.78 $(M + H)^+$; Elemental analysis calcd for $C_{26}H_{16}N_4O_2Br_2 \cdot H_2O$: C, 52.52, H, 3.03, N, 9.43. Found: C, 52.78; H, 3.15; N, 9.56.



Scheme 1 The synthesis route of the receptor 1

Results and discussion

Fluorescent responses toward anions

Firstly, the UV-vis spectral titrations were performed in the dry DMSO solution to assess the anion binding property of the receptor 1. However, the host 1 exhibited neglectable spectral changes likely due to be short of a chromophore. As a result of a 1,10-phenanthroline group in the receptor 1, the anion binding ability of 1 was easily investigated through monitoring the fluorescent emission spectra of the complex 1 upon binding anions. Figure 1 showed the changes in the intensity of fluorescence emission in DMSO with the increase of bromide ions concentration. The receptor 1 (2×10^{-5} mol L^{-1}) displayed two weak fluorescence emission bands at 377 nm, 396 nm, respectively when excited at $\lambda = 368$ nm. The presence of Br^- gave birth to an enhancement in fluorescence intensity with respect to the anion-free solution. The fluorescent enhancement could be rationalized on basis of two signaling transduction mechanisms: (1) inhibition of photoinduced electronic transfer (PET) [16, 17] and (2)

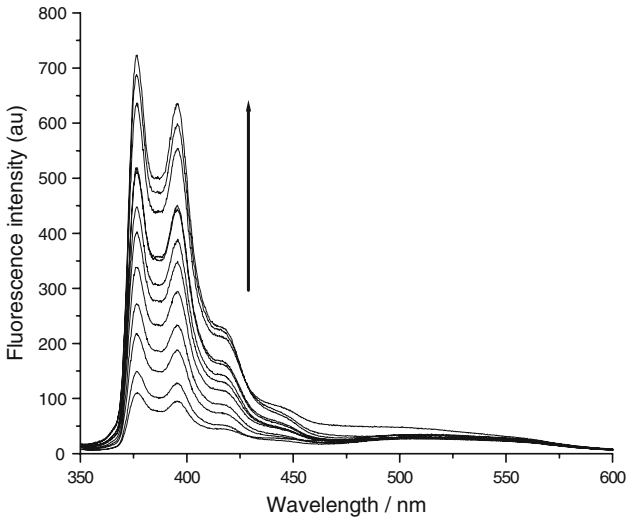


Fig. 1 Fluorescence spectra (excitation at 368 nm) of the receptor 1 (2×10^{-5} mol L^{-1}) in the presence and absence of bromide ion

binding-induced rigidity of the host molecule [17–19]. There were not any changes in the excited and emission wavelengths during the fluorescence titration, which demonstrated a potential photoinduced electronic transfer (PET) signaling transduction occurred. In the first place, prior to the binding process, two nitrogen atoms of the free receptor 1 could form an intramolecular hydrogen bond with hydrogen atoms and thus there would be a photoinduced electronic transfer between the recognition sites and the fluorophore, which resulted in the fluorescence quenching. Upon binding anions, the PET fluorescence quenching process was weakened and in other words the fluorescent enhancement observed resulted from inhibition of PET. In the next place, there were many literatures reported about an increase in emission intensity resulting from a receptor rigidified by complexation and inhibiting vibrational and rotational relaxation modes of nonradiative decay. Similar changes in the fluorescence spectra were observed upon addition of other anions tested such as F^-, Cl^- and AcO^- ions (see Fig. 2). However, addition of $H_2PO_4^-$ and I^- could not lead to any distinct changes in the emission of 1.

Binding constants

Affinity constants of the receptors for anionic species, which were shown in Table 1, were determined by non-linear fitting analyses of the titration curves according to the Eq. 1, 1:1 host–guest complexation [20]

$$I = I_0 + (I_{\lim} - I_0)\left\{c_H + c_G + 1/K_{ass} - \left[(c_H + c_G + 1/K_{ass})^2 - 4\ c_H c_G\right]^{1/2}\right\}/2c_H \quad (1)$$

where, c_G and c_H were the concentration of guest and host, respectively and I was the intensity of emission at certain concentration of host and guest. I_0 was the intensity of emission of host only and $I_{\lim}$ was the maximum intensity of fluorescence of host when gust was added. K_{ass} is the affinity constant of host–guest complexation. Interestingly, the ion which was bond the most strongly by the receptor 1 was not more basic F^- and AcO^- ions but less basic Br^- ion. It became clear early on that the selectivity for special anions could be rationalized on the basis of the guest basicity and shape complementarity between the host and the anionic guests. The more basic F^- and AcO^- ions could bind the host molecule more strongly; however, two binding sites in 1 were more compatible to the size of bromide than to the size of other anions (see Scheme 2) and could bind Br^- through cooperative hydrogen bonding interactions. Consequently, the preference of the receptor 1 for bromide could be ascribed to shape complementarity of complexation, not to basicity of the anion [21].

^{1}H NMR titration

To examine the nature of the interactions between anions and the receptor 1, ^{1}H NMR spectral changes upon addition

Table 1 Association constants (K_{ass} mol^{-1} L) of the receptors 1 with anions in DMSO at 298.2 ± 0.1 K

Anions[a]	F^-	Cl^-	Br^-	I^-	AcO^-	$H_2PO_4^-$
K_{ass}	4 840 (0.9878[b])	1 780 (0.9882)	13 580 (0.9977)	ND[c]	230 (0.9898)	<10

[a] All the anions were added in the form of tetra-*n*-butylammonium (TBA) salts

[b] Correlation coefficient (R^) determined by non-linear fitting analyses

[c] The association constant could not be determined

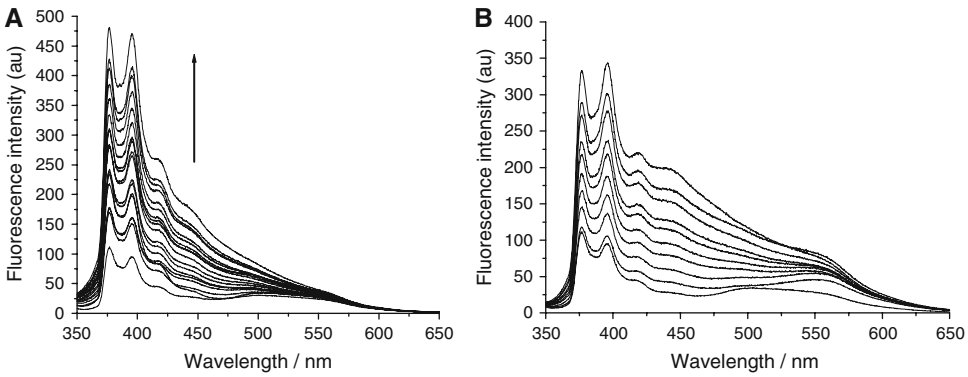
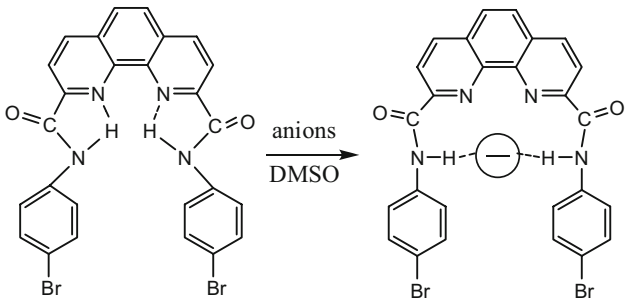


Fig. 2 Fluorescence spectra (excitation at 368 nm) of the receptor 1 (2×10^{-5} mol L^{-1}) in the presence and absence of chloride (**a**) and acetate (**b**) ions



Scheme 2 The proposed anion-receptor binding mode in solution

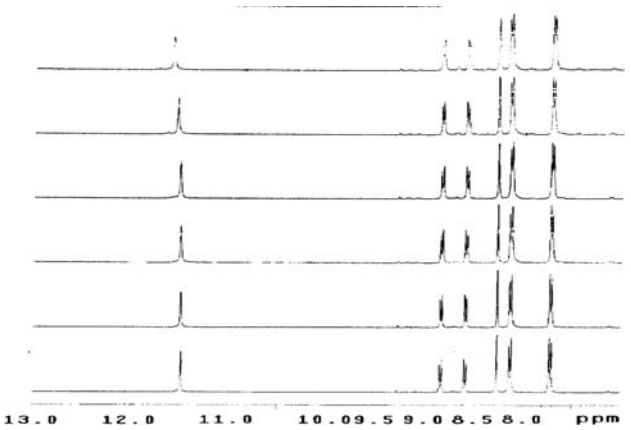


Fig. 3 Plots of ^{1}H NMR spectra of receptor 1 (5×10^{-3} mol L^{-1}) on addition of F^- in DMSO-d_6 (from bottom to top: 0, 0.5, 1.0, 1.5, 2.0, 2.5 equiv., respectively)

of F^- and AcO^- as their tetrabutylammonium salts to the DMSO-d_6 solution of 1 (5×10^{-3} mol L^{-1}) were investigated. Obviously observed from Fig. 3, upon addition of F^-, the N–H proton signal at 11.48 ppm shifted downfield to 11.93 ppm and the other proton signals did not shift at all, suggesting that only N–H moieties as binding sites interacted with F^- through hydrogen bonding [19]. This result further corroborated the hypothesis in fluorescent titration experiments that the binding sites of the receptor 1 cooperatively interacted with anions tested through hydrogen bonding. Similar effects were observed in ^{1}H NMR spectra of 1 upon addition of AcO^- (see Fig. 4). In addition, ^{1}H NMR titrations of the receptor 1 with Br^- were also carried out in DMSO-d_6 solution. Just as the Fig. 5 showed, addition of two equiv. Br^- resulted in the slight shift changes and the notable changes from 11.47 ppm to 11.90 ppm were observed upon addition of 60 equiv. Br^- ions. The results indicated that the strong hydrogen bonding interactions occurred between the host molecule 1 and the guest Br^- anion. As mentioned above, the proposed binding mode in solution was shown in Scheme 2.

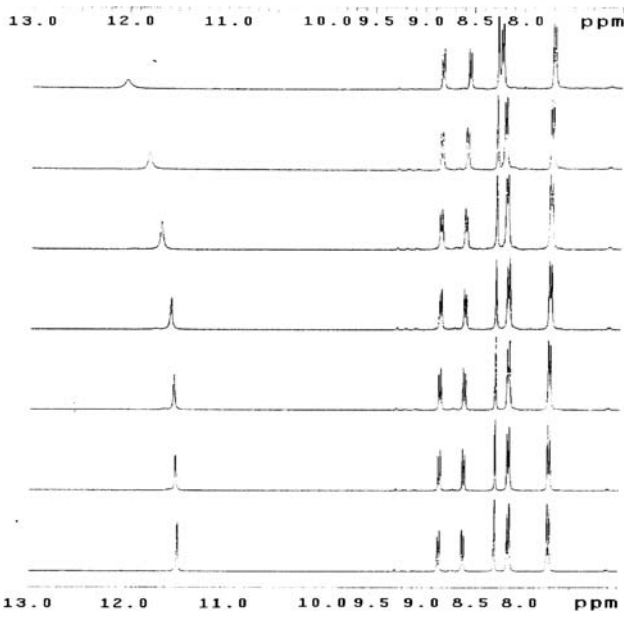


Fig. 4 Plots of ^{1}H NMR spectra of receptor 1 (5×10^{-3} mol L^{-1}) on addition of AcO^- in DMSO-d_6 (from bottom to top: 0, 0.5, 1.0, 1.5, 2.0, 2.5, 100 equiv., respectively)

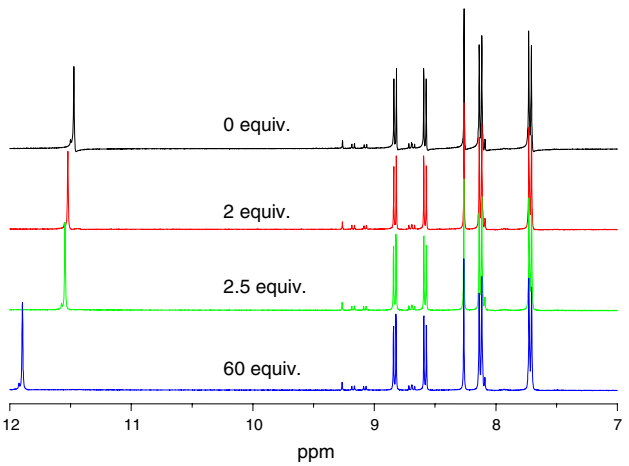


Fig. 5 Plots of ^{1}H NMR spectra of receptor 1 (5×10^{-3} mol L^{-1}) on addition of Br^- in DMSO-d_6

Conclusion

In conclusion, a selective fluorescent sensor for bromide, *N*,*N*′-di-*p*-bromophenyl-1,10-phenanthroline-2, 9-diamide was synthesized and characterized. In DMSO, fluorescent titrations of the receptor 1 with bromide demonstrated the presence of anion–host interaction species with binding constant K_{ass} = 13 580 mol L^{-1}.

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