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New color chemosensors for cyanide based on water soluble azo dyes

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ABSTRACT

Cyanide detection in pure water is important for many applications. We present a novel type of chemodosimeter azo dye developed on the basis of the benzophenone as the electrophilic receptor of the cyanide anion and a saccharidic moiety to render the dye water soluble. This chemodosimeter is found to be highly selective and tunable toward only cyanide in pure water.

1. Introduction

A few decades ago, there was a general feeling that nature could effectively handle hazardous substances. Although nowadays human beings are more concerned for their sensitive natural environment, pollution is still a problem. Experts estimate that the industrial processes introduce up to a million different pollutants into the atmosphere and the aquatic ecosystem.[1]

Cyanides are categorized within these substances, which are considered one of the most lethal poisons known.[2–11] The absorption is the mechanism of toxicity for cyanide which occurs through the lungs, gastrointestinal track, and skin. Cyanide is highly toxic due to the inhibition of the oxygen utilization by cells, binding with ferric iron in cytochrome oxidase and blocking the oxidative process of cells. The tissues with the highest oxygen requirements (brain, heart, and lungs) are the most affected by acute poisoning. Even though cyanide poisoning is not common, it can occur because of smoke inhalation from residential and industrial fires and among people who work in the metal, mining, electroplating, jewellery manufacture, and X-ray film recovery trades.[1–15] Numerous chemical and physiochemical methods for the detection and determination of cyanides, such as potentiometry, chromatography, spectrophotometry, flow injection, and electrochemical analyses are used,[1–14] but only potentiometric determination has been reported as offering continuous cyanide monitoring.[15]

Several methods have previously been developed to detect cyanide by using a wide diversity of experimental protocols and detection techniques.[16] Methods based on anion-induced changes of the optical properties (either absorption or emission) of receptors are especially attractive. Recent examples which use this approach involve the use of large chemosensors based on Ru(II)-containing pyrrolylquinoxalines,[17] Zn(II) complexes of porphyrin derivatives,[18] boronic acid groups,[19] trifluoroacetophenone derivatives,[20] and Re(I) polypyridyl complexes,[21] among others.[22] However some of these systems need to be carried out in organic solvents or a mixture of organic solvents and water, which limits their applicability for the analyses of 'real' samples that are often in aqueous solution.

Recently, a new category of water soluble dyes was developed as dyeing agents in water.[23] The water solubility was obtained by the glycoconjugation of the starting organic dyes with lactose or with its monosaccharidic components, glucose or galactose, which is the most important characteristic that we aim to transfer to (or improve in) the organic cyanide chemodosimeters.

From this perspective, we report herein the synthesis of new water soluble glycoconjugated azo dyes based on benzophenone as the cyanide receptor, and their ability to selectively detect cyanide in pure water.

2. Results and discussion

Our approach to a new type of cyanide chemodosimeters is depicted in Figure 1.

A latent chromogenic moiety with a carbonyl group (–COR) may comprise a new type of chemodosimeters for cyanide because cyanide has strong affinity toward the carbonyl group and thus attack cyanide of the carbonyl group and may trigger the 'latent' chromo-

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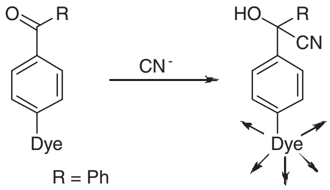


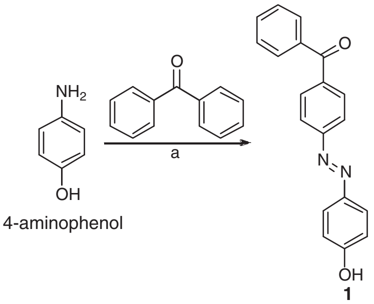
Figure 1. A schematic diagram for the displacement approach to new chemodosimeters.

genic moiety into an 'active' state. To evaluate this mechanism, we focused our attention to the electrophilic character of the carbonyl group of the benzophenone which can be introduced as an electrophile for the anion in an azo dye functional group as a chromophore.

Scheme 1 represents the synthesis of an azo dye **1** possessing a benzophenone unit. The synthesis was carried out by treating the commercial 4-aminophenol with sodium nitrite in acidic medium at 0 °C to form the corresponding diazonium salt, followed by treating with the benzophenone.

The azoic dye **1** was not soluble in water, insensitive to warming, stirring, powdering, and microwaving. All attempts to solubilize it led to two-phase systems, with the water phase almost completely clear and colorless. To render the dyes **1** water-soluble, we attempted to glycoconjugate it with saccharidic moiety. For this purpose, the protected ethereal lactose **2e** was prepared from α,D-lactose **2** depending on the procedure reported in the literature (Scheme 2).[22] Next, the oxygen atom of the hydroxyl group in dye **1** was linked to the carbon of the bromine atom of the protected sugar **2e** in the presence of KOH as the strong inorganic base and 18-crown-6 as the phase transfer agent. We used non-anhydrous THF as the solvent due to its help in dissolving KOH without affecting the yield by competing with the crown ether.

The final step was the deprotection of this last compound using TFA, which results in the isolation of the water soluble chemodosimeter **4** in good yield (Scheme 3).



Scheme 1. Synthetic process of compound **1**. Reagents and conditions: (a) $NaNO_2$, HCl 37%, H_2O, 0 °C to rt, 12 h.

Compound **4** was characterized by spectroscopic and analytical techniques such as the ^{1}H and ^{13}C NMR spectra. The integration and multiplicity in the ^{1}H NMR spectra were indicative of the presence of both aromatic and glucidic rings in **4**. The resonance in ^{13}C NMR spectra of the samples at 193.2 ppm was assigned to the carbonyl carbon of the benzophenone unit.

2.1. UV–vis spectra studies

UV–vis absorption spectra of the newly generated glyco-conjugated dyes are crucial because the modified dyes should display the same color as the starting materials to ensure that the chromophore is not affected by the glycoconjugation process. As in the case of dye obtained by the attachment of glucide to a phenolic hydroxyl group of dye **1**, the UV–vis spectra of the starting dye **1** and the glycoconjugated dyes **4** in DMSO are shown in Table 1. The results reported in Table 1 show that λ_{max} does not exhibit any significant shift after the glycoconjugation with the glucide units. Furthermore, molar extinction coefficient values can be considered constant.

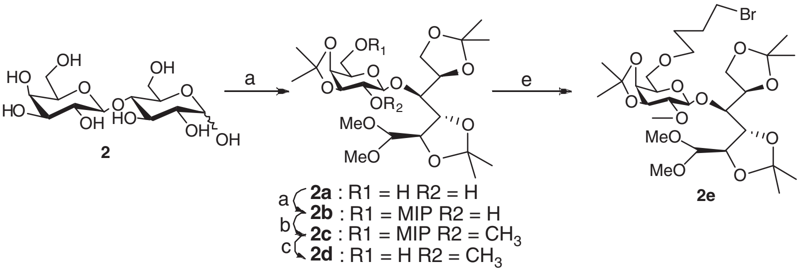
2.2. Studies of the anion-dye interaction in solution

As a first step, the chromogenic sensing ability of **1** was studied in DMSO in the presence of six different anions namely, F^-, Cl^-, CH_3COO^-, $H_2PO_4{}^-$, SCN^-, and CN^-. Figure 2 shows that only the addition of one equivalent of F^- and CN^- induced distinct spectra changes, while other anions such Cl^-, CH_3COO^-, $H_2PO_4{}^-$ and SCN^- did not induce any color changes even in large excess.

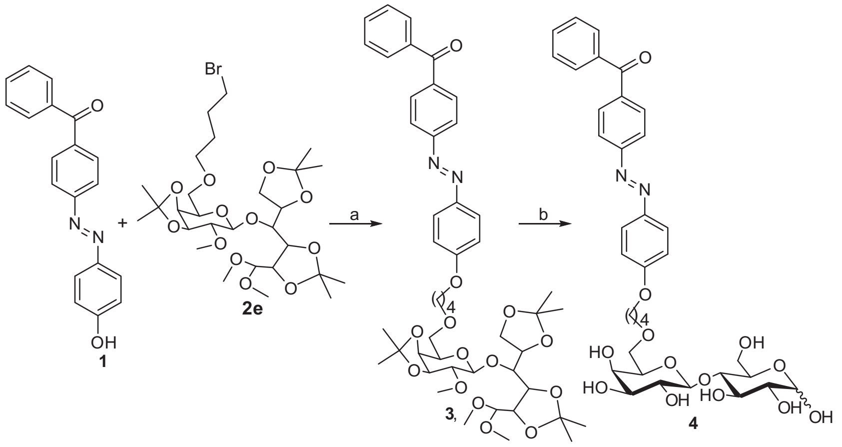
The ^{1}H NMR spectrum of the initial anion-free solution of dye **1** showed four multiplets between $\delta = 8.15$ ppm and $\delta = 7.06$ ppm, which correspond to the protons of the three aromatic rings, and one singlet at $\delta = 5.31$ ppm which corresponds to the protons of the aromatic alcohols: by adding the cyanide and the fluoride to this solution, a new singlet appeared at $\delta = 3.77$ ppm. Therefore, the results of ^{1}H NMR prove that the exchange color is due to the formation of the cyanohydrin and fluorohydrin during the nucleophilic attack of cyanide and fluoride anions toward the carbonyl group of dye **1** (Fig. 3).

In spite of the interesting reactivity of dye **1** found in DMSO, it shows poor selectivity, with respect to F^-. To take benefit of the favorable features of **1** as a chemodosimeter, and to improve its selectivity towards CN^-, we tested the reactivity of the glycoconjugated form of **1** (dye **4**) in pure water to investigate the anion nucleophility and the sensing response.

The anion sensing properties of the glycoconjugated dyes **4** were studied in solution by using water as the solvent. An intense absorption band for the $\pi \rightarrow \pi^*$ transition of 4-glycoconjugated azophenyl chromophore appears at $\lambda_{max} = 356$ nm, while it is very weak at $\lambda_{max} = 455$ nm for **4**. The anions selected for these studies were F^-, Cl^-, Br^- CH_3COO^-, $H_2PO_4{}^-$, SCN^-, and CN^-. A solution of **4**



Scheme 2. Conversion of lactose **2** into the 4-bromo butyl-protected lactose **2e**. Reagents and conditions: (a) DMP, TsOH, 80 °C, 5 h (b) DMP, TsOH, 80 °C, 1.5 h (c) MeI, NaH, DMF, 0 °C to rt, 2 h (d) H_2O/MeOH (1:10), 1.5 h, 80 °C (e) 1,4-dibromo butane, KOH, 18 crown 6, THF, rt, 12 h.



Scheme 3. Glycoconjugation of chemodosimeter **1**. Reagents and conditions: (a) KOH, 18-crown-6, THF, rt, 12 h (b) TFA, rt, 3 h.

Table 1
Spectoscopic data for the dyes **1** and **4**

Dyes	$\lambda_{\max}$ (nm)	log (ε(max)/M^{-1} cm^{-1})
1	356	4.0170
4	356	4.0100

in water (0.5 mM) was treated at room temperature with a constant amount of the different anions (one equivalent added as tetrabutylammonium salts). As showed in the Figure 4, the addition of CN^- only causes a change in the UV–vs absorption spectrum of dye **4**. The intensity of the absorption bands increases by emerging a new band at 455 nm. This was perceived by naked-eye observation: a color change from colorless to yellow was only observed upon addition of cyanide (Fig. 4).

It is known that the nucleophilic character of different species is solvent-dependent. In fact, the protic solvents decrease the anion's nucleophilicity by hydrogen bonding to the nucleophile one pair (solvation effects). A suitable solvent induces the selectivity enhancement by using water; which means a solvent of special importance, since it is a suitable media for testing chromo- sensing probes for anions of environmental interest. In pure DMSO solution, dye **1** react with the anions CN^- and F^-, but in water, the glycoconjugated form of **1** (dye **4**) react selectively with CN^- by the changing of the solution color from colorless to yellow as in the case of the dye **1** in DMSO.

This selective response to cyanide is an attractive feature. Since the cyanide is a highly toxic anion, it is still in use widely in different applications, that is, electroplating, mining, metallurgy, etc. Moreover, cyanide can also be present in certain foods such as cassava roots, pits of certain fruits and bitter almonds. Actually, there are relatively few examples of colorimetric probes for cyanide[24] compared to the number of chromogenic chemosensors for certain anions such as fluoride or carboxylates.[24] However, because of its wide use and serious toxicity, the development of new chemosensors for cyanide in water offers many interests[25] such as rapid and screening applications. In this field, chromogenic optical probes will play an important role.

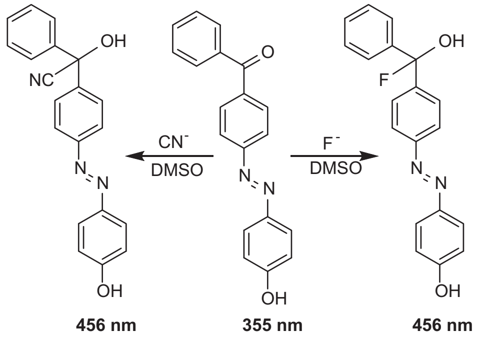


Figure 3. Hosts and a plausible sensing mechanism of cyanide and fluoride.

To analyze quantitatively the changes observed in water by adding CN^- increasingly, a series of titrations using UV–vs spectroscopy will be carried out on dye **4**. An example of the titration curves obtained upon the addition of increasing amounts of cyanide to dye **4** is illustrated in Figure 5. The changes observed in the absorption spectrum of **4** show that two species are present in the solution, where their proportions depend on the amount of cyanide added. In the absence of anion, compound **4** in water has a $\lambda_{\max}$ value of 356 nm. Upon addition of cyanide, the new

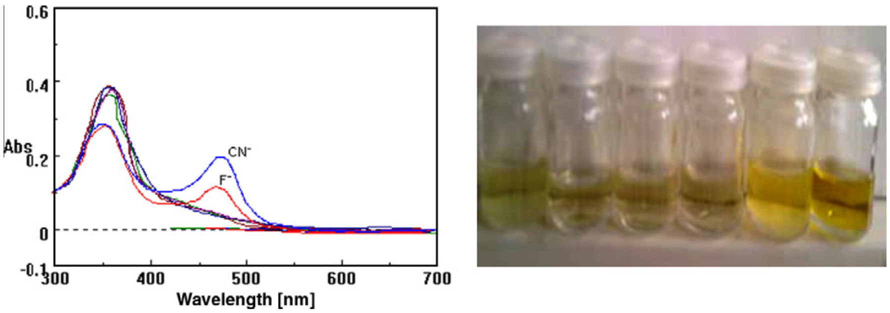


Figure 2. Absorption spectra and color change when dye 1 (0.5 mM) was treated with various analytes (vials from the left:, Cl^-, CH_3COO^-, $H_2PO_4^-$, SCN^-, F^- and CN^- as Bu_4N^+ salts) in DMSO.

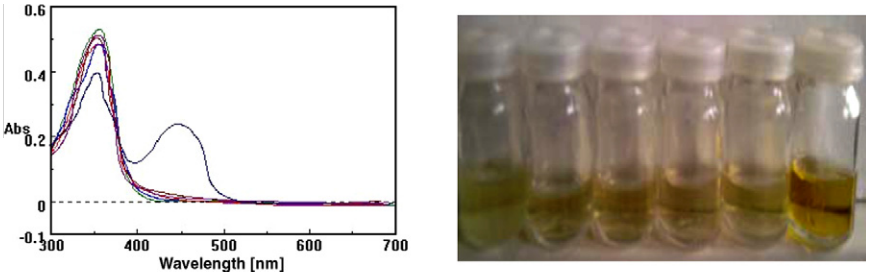


Figure 4. Absorption spectra and color changes when dye **7** (0.5 mM) was treated with various analytes (vials from the left:, Cl–, Br^- CH3COO$^-$, $H_2PO_4^-$, SCN^-, F^- and CN^- as Bu_4N^+ salts) in water.

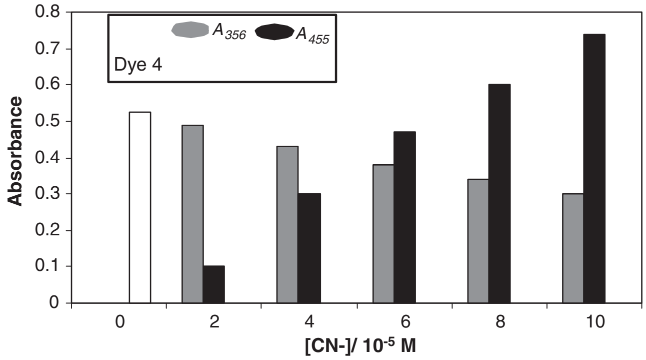


Figure 5. Absorption changes of **4** upon the addition of increasing amounts of cyanide using a 2×10^{-5} M solution of **4** in pure water.

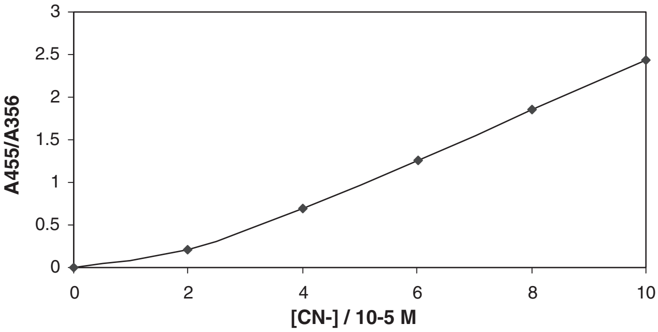


Figure 6. Plot of the absorption ratio between 356 nm and 455 nm (A_{455}/A_{356}) versus Concentration of CN^- in water.

bond at $\lambda_{max} = 455$ nm corresponds to the absorption of the new species.

Figure 6 shows a near-linear correlation between absorption ratios at 455 nm and those at 356 nm (A_{455}/A_{356}) and cyanide concentration in water. This demonstrates the potential utility of sensor **4** for calibrating and determining cyanide ion concentration in the pure water, where the presence of other halide ions does not cause any changes in the absorption of **4** (shown in Fig 3). Furthermore, the lowest concentration of CN^- that can be detected is 2.0×10^{-5} M, when the used concentration of dye **4** is 1.0×10^{-5} M. Consequently, A_{455}/A_{356} will increase linearly with the concentration of CN^-.

3. Conclusion

In summary, we have reported the use of water soluble azo dye as probes for the detection of selected anions. In particular, a selective chromo detection of cyanide was reached in water to the ppm level due to the selective reaction of this anion with selected benzophenone glycoconjugated azo dye. It is a simple method, and it allows a selective detection of very low cyanide concentration by the naked eye.

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Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tetlet.2010.08.098.

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