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A selective chromogenic reagent for cyanide determination

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Received (in Cambridge, UK) 4th July 2002, Accepted 28th August 2002
First published as an Advance Article on the web 11th September 2002

A chromogenic reagent for cyanide determination in water based on the reaction of this anion with a squaraine derivative functionalized with ether chains has been developed.

Cyanide is probably one of the more toxic inorganic anions one can find. Despite its acute toxicity, cyanide or hydrogen cyanide are used in a large number of applications, for instance to make certain synthetic fibres and resins, in herbicides, in gold mining, *etc*. Due to its wide range of application and its serious toxicity the development of new molecules for cyanide determination or sensing may be of interest.[1]

There is increasing attention on the development of anion chemosensors able to transform microscopic anion interactions into a suitable macroscopic response.[2] One of the most interesting output signals is the visible absorption, because the instrumentation is widely available, but also because it would be possible to sense target species with the naked eye. Different approaches have been envisaged for the design of chromogenic probes for anion sensing. Most of them are based on the coupling of dyes to anion binding sites[3] or the use of displacement reactions.[4] More recently we have used anion-induced cyclization processes for the colorimetric detection of anions.[5] However, many of these colorimetric chemosensors only display colour changes in organic solution and can not be used in aqueous environments. An alternative method is based on the use of specific reactions (usually irreversible) produced by target anions.[6] This idea tries to take advantage of the selective reactivity that certain anions display. Following this approach we have selected a particular feature of the cyanide anion: its nucleophilic character, and report here a selective probe for cyanide determination in water using a colorimetric method.

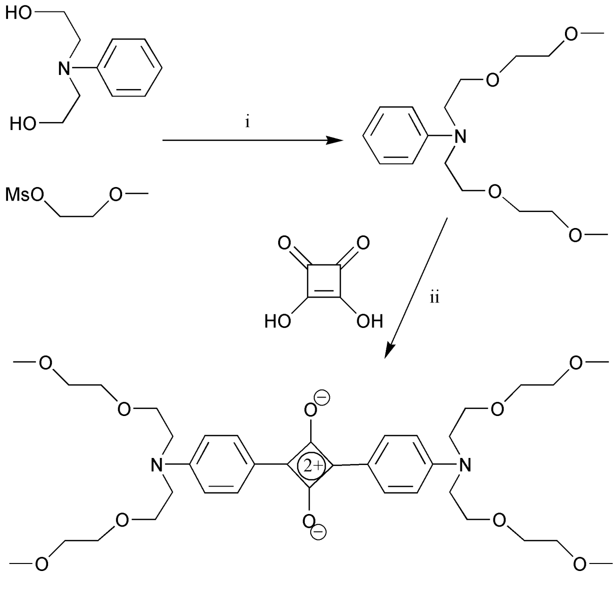
Among recent developments in the field of chromogenic systems for anions two recent approaches to cyanide sensing have been reported by Kim and Anzenbacher,[7] however, these only gave colour changes in dichloromethane and dichloromethane : acetonitrile solutions and are not highly selective.

Our approach is based on the decolouration selectively observed upon nucleophilic attack of cyanide to a functionalised squaraine. We focused our attention on squaraine dyes because of their peculiar chemical and physical properties. They are known to show very intense (ε up to 100 000) and sharp bands near the IR which is a region of special interest for the development of optical instrumentation and because the number of potential coloured interferences is lower than when the absorption is near the UV. The squaraine derivative we have used (see Scheme 1) is built up by two N-functionalised anilinium groups anchored to a central four-atom ring. The colour in this dye is due to a charge transfer band between the donor anilinium moieties and the central acceptor four-membered ring.[8] The atoms in that acceptor four-atom ring (see Scheme 1) are electron-deficient and should be able to undergo nucleophilic attack. As stated above cyanide is a well-known nucleophile and we believed that a nucleophilic addition to the ring could result in selective detection of this toxic anion.

Squaraine dyes have found several fields of application[9] but as far as we know, they have never been used as reagents for anion determination. One probable reason for this is because one of the main drawbacks of working with squaraine dyes is their very low solubility, both in organic solvents and in water. For instance, a compound similar to L[1] but synthesised from *N*,*N*-dimethylaniline is just sparingly soluble in dichloromethane and completely insoluble in water. In order to avoid this problem we have synthesised L[1] which is a derivative functionalised with ether chains to improve its solubility in water. Ether chains have been extensively applied as polar groups for instance in non-ionic surfactants and in crown ethers.

L[1] was synthesised (see Scheme 1) by a two step reaction. In the first step, the mesylated derivative of 2-methoxyethanol with *N*-phenyldiethanolamine gave *N*,*N*-di(ethyl-2-(2-methoxyethoxy))aniline. Two equivalents of this compound react with one equivalent of squaric acid with azeotropic removal of water[10] to yield L[1] (18%). The absorption spectrum of L[1] shows a sharp and very intense band with a maximum at 641 nm in acetonitrile (log ε = 5.08).

L[1] has drastically changed its solubility properties when compared with other reported squaraine derivatives. Thus, L[1] is soluble in a larger number of polar organic solvents; it is soluble in water and in all the range of acetonitrile–water mixture compositions. The ligand is stable for months as a solid or in acetonitrile solution but it undergoes slow decomposition in water-containing solutions. In a first step, the chromogenic sensing ability of L[1] was studied in acetonitrile in the presence of the anions F^-, Cl^-, Br^-, I^-, NO_3^-, $H_2PO_4^-$, HSO_4^-, Ac^-, Bz^-, CN^- and SCN^-. Among these, only cyanide is able to affect the band at 641 nm, as can be seen in Fig. 1. The decolouration process is not instantaneous but it increases with time and with the number of cyanide equivalents. ^1H NMR data for L[1] in acetonitrile upon cyanide addition is consistent with



Scheme 1 Synthesis of L[1]. i: CH_3CN, reflux; ii: BuOH/tol.

DOI: 10.1039/b206500b

Fig. 1 L^1 in acetonitrile ($[L^1] = 3.0 \times 10^{-5}$ M) in the presence of 5 equivalents of anions, from left to right, F^-, Cl^-, Br^-, I^-, NO_3^-, $H_2PO_4^-$, HSO_4^-, Ac^-, Bz^-, SCN^-, CN^- and no anion.

cyanide attack on a carbon of the four-atom squaraine ring next to the phenyl group.[11] This would produce both loss of the acceptor character of the ring and rupture of the electronic delocalisation with the consequent disappearance of the 641 nm charge transfer band.

In order to examine the potential use of the molecular chromogenic reagent L^1 for the determination of cyanide in aqueous solutions further experiments were carried out. The studies were performed buffering to pH 9.5 (0.01 M of TRIS [tris(hydroxymethyl)aminomethane]) aqueous cyanide solutions containing different amounts of cyanide. Eight parts of these aqueous solutions were mixed up with two portions of an acetonitrile solution containing the L^1 chromogenic reagent (concentration of L^1 in the water : acetonitrile 80 : 20 v/v final mixture was 10^{-5} M). Like in acetonitrile solutions it was observed that the variation in the absorbance was proportional to the cyanide concentration and that it changed with time. This can be seen in Fig. 2 which shows the colour of L^1 solutions in the presence of different cyanide concentrations after 18 minutes once the mixture was set. Additionally Fig. 3 shows the plot of the logarithm of the absorbance of the solutions in Fig. 2 *versus* the cyanide concentration. A linear response was observed in the 1×10^{-5}–3×10^{-4} M range. A detection limit as low as 0.1 ppm was found for the detection of cyanide in water.[12]

Fig. 2 H_2O : ACN 80 : 20, from left to right $[CN^-] = 0, 1, 3, 5, 8, 11, 14, 18, 22, 26, 30$ and 40×10^{-5} M, in presence of TRIS 0.01 M after 18 minutes of reaction, $[L] = 1.00 \times 10^{-5}$ M.

The fact that the reaction between L^1 and cyanide is not instantaneous but a function of the time and the linear response found between the logarithm of the absorbance and the concentration of cyanide (see Fig. 3) indicates a second-order process related to the reaction between L^1 and cyanide anion. The reaction has a rate constant in water : acetonitrile 80 : 20 v/v mixtures of 2.73 M^{-1} s^{-1} at 20 °C. The reaction can not be carried out when the pH is more basic because then there is rapid decolouration of L^1 even in the absence of cyanide probably due to the nucleophilic attack of the OH^- on the four-atom ring of the squaraine dye.

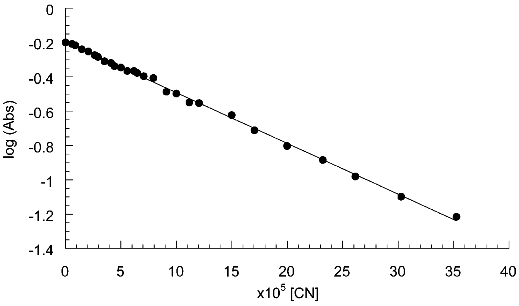


Fig. 3 Log (Abs) *versus* the concentration of cyanide in water : acetonitrile 80 : 20 v/v, at pH 9.5 (TRIS 0.01 M) after 18 minutes of reaction, $[L^1] = 1.00 \times 10^{-5}$ M (20 °C).

We have also confirmed in preliminary studies that L^1 can act as a selective chromogenic reagent for the quantitative determination of cyanide in water samples. Thus in a typical experiment a known amount of cyanide was added to water also containing 28.7 ppm of Na^+, 23.4 ppm of K^+, 44.3 ppm of Cl^-, 12.3 ppm of NO_3^- and 19.3 ppm of SO_4^{2-}. This mixture containing a concentration of cyanide of 2.2 ppm was mixed with acetonitrile and following the method outlined above and using the calibration curve in Fig. 3 a concentration of CN^- of 2.5 ppm was determined. Further studies are being carried out in order to determine the potential use of L^1 as a chromogenic reagent for easy-to-use colorimetric probes for cyanide determination in a wide range of locations. Studies are also under way into the use of other dyes also containing highly electrophilic acceptor units as chromogenic reagents for cyanide.

In summary we have reported a new colorimetric method for determination of cyanide in water samples based on the specific reaction of this anion with a water soluble squaraine derivative. The method is easy and allows detection by the naked eye of low cyanide concentrations.

We should like to thank the DGICYT (PB98-1430-C02-02 and AMB99-0504-C02-01) for support. J.V.R.L. also thanks the Ministerio de Educación, Cultura y Deporte for a Doctoral Fellowship.

Notes and references

1 C. O. Ikediobi, L. Wen and L. M. Latinwo, *Am. Environ. Lab.*, 1997, **9**, 20.

2 F. P. Schmidtchen and M. Berger, *Chem. Rev.*, 1997, **97**, 1609; P. D. Beer and P. A. Gale, *Angew. Chem., Int. Ed.*, 2001, **40**, 486; P. A. Gale, *Coord. Chem. Rev.*, 2000, **199**, 181; P. A. Gale, *Coord. Chem. Rev.*, 2001, **213**, 79.

3 D. Jimenez, R. Martinez-Mañez, F. Sancenon and J. Soto, *Tetrahedron Lett.*, 2002, **43**, 2823; H. Miyaji, W. Sato and J. L. Sessler, *Angew. Chem., Int. Ed.*, 2000, **39**, 1777; D. H. Lee, H. Y. Lee, K. H. Lee and J. I. Hong, *Chem. Commun.*, 2001, 1188; F. Sancenón, R. Martínez-Máñez and J. Soto, *Angew. Chem., Int. Ed.*, 2002, **41**, 1416; H. Miyaji and J. L. Sessler, *Angew. Chem., Int. Ed.*, 2001, **40**, 154.

4 S. L. Wiskur, H. Ait-Haddou, J. J. Lavigne and E. V. Anslyn, *Acc. Chem. Res.*, 2001, **34**, 963; H. Ait-Haddou, S. L. Wiskur, V. M. Lynch and E. V. Anslyn, *J. Am. Chem. Soc.*, 2001, **123**, 11296.

5 F. Sancenón, A. B. Descalzo, R. Martínez-Máñez, M. A. Miranda and J. Soto, *Angew. Chem., Int. Ed.*, 2001, **40**, 2640.

6 A. B. Descalzo, D. Jiménez, J. El Haskouri, D. Beltrán, P. Amorós, M. D. Marcos, R. Martinez-Mañez and J. Soto, *Chem. Commun.*, 2002, 562.

7 Y. H. Kim and J. I. Hong, *Chem. Commun.*, 2002, 512; P. Anzenbacher, Jr., D. S. Tyson, K. Jursíková and F. N. Castellano, *J. Am. Chem. Soc.*, 2002, **124**, 6232.

8 R. W. Bigelow and H. J. Freund, *J. Chem. Phys.*, 1986, **107**, 159.

9 See for example: A. C. Tam and R. D. Balanson, *IBM J. Res. Dev.*, 1982, **26**, 186; A. P. Piechowski, G. R. Bird, D. L. Morel and E. L. Stogryn, *J. Phys. Chem.*, 1984, **88**, 934; V. P. Jipson and C. R. Jones, *J. Vac. Sci. Technol.*, 1981, **18**, 105; G. J. Ashwell, G. Jefferies, D. G. Hamilton, D. E. Lynch, M. P. S. Roberts, G. S. Bahra and C. R. Brown, *Nature*, 1995, **375**, 385.

10 H. E. Sprenger and W. Ziegenbein, *Angew. Chem., Int. Ed. Engl.*, 1968, **7**, 530.

11 ^1H NMR of L^1 in acetonitrile gave in the aromatic region two doublets (at 8.25 and 7.60 ppm) whereas upon cyanide addition four doublets are observed (centred at 7.60, 7.24, 6.75 and 6.72 ppm). The ^{13}C NMR of L^1 in the aromatic region gave as expected 6 signals at 188.5, 183.1, 153.7, 133.1, 119.9 and 112.5. Upon cyanide addition there is a loss of symmetry. The most characteristic feature upon cyanide addition is that the signals of the central four menber ring at 188.55 and 183.13 ppm disappear and appear a total of 4 signals at 176.3, 131.5, 111.9, 52.1 and a signal at 126.3 attributable to the carbon of the CN group.

12 The US Environmental Protection Agency (EPA) has set the so called Maximum Contaminan Level Goals for cyanide in drinking water to 0.2 ppm.