Tetrahedron 93 (2021) 132312

Contents lists available at ScienceDirect

Tetrahedron

journal homepage: www.elsevier.com/locate/tet

Selective colorimetric sensor for cyanide anion based on 1hydroxyanthraquinone



Tetrahedror

Timofey P. Martyanov ^{a, *}, Alexandra A. Kudrevatykh ^b, Evgeny N. Ushakov ^a, Denis V. Korchagin ^a, Ilia V. Sulimenkov ^c, Sergey G. Vasil'ev ^{a, d}, Sergey P. Gromov ^e, Lyubov S. Klimenko ^b

^a Institute of Problems of Chemical Physics, Russian Academy of Sciences, Chernogolovka, Moscow Region, 142432, Russian Federation

^b Yugra State University, ul. Chekhova 16, Khanty-Mansiysk, 628012, Russian Federation

^c Chernogolovka Branch of the N.N. Semenov Federal Research Center for Chemical Physics, Russian Academy of Sciences, Chernogolovka, Moscow Region, 142432, Russian Federation

^d Science Center in Chernogolovka, Russian Academy of Sciences, Chernogolovka, Moscow Region, 142432, Russian Federation

^e Photochemistry Center of RAS, FSRC "Crystallography and Photonics", Russian Academy of Sciences, Novatorov str. 7A-1, Moscow, 119421, Russian Federation

ARTICLE INFO

Article history: Received 23 April 2021 Received in revised form 27 May 2021 Accepted 6 June 2021 Available online 30 June 2021

Keywords: Cyanide Hydroxyanthraquinone Anthraquinone Chemosensor Chemoreceptor Chromogenic probe

ABSTRACT

The article addresses the synthesis, structure and properties of 2-benzovlamino-1hydroxyanthraquinone (1a), which can function as a selective colorimetric sensor for the cyanide anion in aqueous media. Compound 1a was prepared in two simple steps in good yield and its structure was confirmed by X-ray diffraction analysis. UV-Vis and NMR spectroscopy, mass spectrometry and quantum chemistry studies revealed that in MeCN-H₂O mixtures (95:5, v/v), cyanide ionizes the hydroxyl group of the anthraquinone, which results in a strong bathochromic effect. The association constant of cyanide anion with **1a** was measured to be $10^{4.88}$ M⁻¹; the detection limit is about 0.22 μ M. The presence of a benzovlamino group at position 2 of the anthraguinone core has a stabilizing effect on the anionic form of **1a** due to the hydrogen bonding between the amide hydrogen atom and the oxygen atom of the ionized hydroxyl group.

© 2021 Elsevier Ltd. All rights reserved.

1. Introduction

Modern researches in chemistry are increasingly involving the extensive application of selective and sensitive methods for detecting anions owing to the latter's pivotal role in environmental, industrial and biological processes [1–4]. The detection of cyanide, a chemical compound that is well known for its extremely high physiological toxicity and presence as an environmental pollutant due to its widespread use in photography, gold mining and various petrochemical industries, has become a top priority [5–7]. In this concern, the development of simple and affordable methods for

* Corresponding author.

detecting cyanide is an urgent task that can be solved by using optical chemosensors. To date, a great variety of colorimetric and fluorescent chemosensors for cyanide have been developed [8-10] that allow rapid analysis with a high selectivity and a low detection threshold.

According to the literature [11], a colorimetric sensor is constructed by combining a chromophore and an anion binding unit. In many cases, cyanide is bound by H-bond donors (OH, NH) through association with hydrogen atoms, which ultimately can lead to deprotonation of the chemosensor molecule [12–14]. Fragments containing an NH unit, such as urea, thiourea and amides, are often introduced into the chemosensor structure to facilitate binding to anions [2]. Interaction with the analyte induces intramolecular charge transfer and leads to a change in the electronic absorption spectrum of the chromophore. Another common type of cyanide binding is its addition to the C=C or C=O double bond [9]. In this case, anion-induced spectral changes occur due to a change in the conjugated π -system of the chromophore. The key to obtaining

E-mail addresses: martyanov.t@gmail.com (T.P. Martyanov), alexandra. korolkova@mail.ru (A.A. Kudrevatykh), e.n.ushakov@gmail.com (E.N. Ushakov), korden@icp.ac.ru (D.V. Korchagin), soulimenkov@mail.ru (I.V. Sulimenkov), viesssw@mail.ru (S.G. Vasil'ev), spgromov@mail.ru (S.P. Gromov), l_klimenko@ ugrasu.ru (L.S. Klimenko).



1a: R¹ = OH, R² = NHCOPh **1b:** R¹ = OH, R² = H **1c:** R¹ = H, R² = NHCOPh **1d:** R¹ = H, R² = NHCOCF₃

Chart 1. Discussed compounds.

chemosensors with specified parameters is a detailed study of the physical and chemical characteristics of the sensor—analyte binding process, justification of the design features and subsequent synthesis. In terms of practical application, a good receptor should not only be highly selective and sensitive, but also easy to obtain and simple to operate. Commercially available quinone derivatives are widely used as signaling units in colorimetric molecular sensors for anions [15].

It has been previously reported [16] that anthraquinone **1d** (Chart 1) bearing an NHCOCF₃ group at position 2 is able to add CN⁻ at the double carbonyl bond of the NHC=O unit. We hypothesized that the formation of a similar adduct in the case of 1-hydroxy-2-amide derivatives of anthraquinone, such as compound **1a** (Chart 1), would stabilize the *ana*-quinoid form (1,10-anthraquinone) due to the electron-donating nature of the substituent at position 2 of the adduct and, thereby, the interaction with CN⁻ would cause stronger spectral changes.

The objects of this study were 2-benzoylamino-1hydroxyanthraquinone (**1a**) and two substructural compounds: 1hydroxyanthraquinone (**1b**) and 2-benzoylaminoanthraquinone (**1c**). The effect of additives of various tetrabutylammonium (TBA) salts on the absorption spectra of water-acetonitrile solutions of anthraquinone derivatives $1\mathbf{a} - \mathbf{c}$ was studied. The reason for the strong color changes observed upon the addition of the TBACN salt to solutions of compound $1\mathbf{a}$ was determined using a combination of different methods: spectrophotometry, mass spectrometry, NMR spectroscopy, and quantum chemical calculations.

2. Experimental

2.1. Materials and measurements

¹H and ¹³C NMR spectra were recorded on a Bruker AVANCE III 500 MHz BioSpin (502.00 and 125.78 MHz, respectively) in CDCl₃, DMSO-*d*₆ or MeCN-*d*₃–DMSO-*d*₆ (9:1, v/v), using the solvent as the internal standard ($\delta_{\rm H}$ 7.26, 2.50 and 1.94 ppm respectively, $\delta_{\rm C}$ 77.16 ppm for CDCl₃). Chemical shifts were measured to an accuracy of 0.01 ppm, and spin-spin coupling constants were determined to an accuracy of ±0.1 Hz. IR spectra were obtained on a Spectrum One FT-IR (PerkinElmer) in KBr pellet. Electronic absorption spectra were recorded on a Specord M40 spectrophotometer in quartz cells with ground-in stoppers.

Electrospray ionization (ESI) mass spectra were acquired using an Exactive Orbitrap mass spectrometer (ThermoFisher Scientific, Germany) and a home-made electrospray ion source. The working resolution of the mass spectrometer in the reported experiments was 10000 (FWHM), the accuracy of *m/z* values measurement was better than 5 ppm, and the mass spectrum registration time was 1 min. The electrospray ion source characteristics were as follows: quartz capillary inner diameter 50 μ m, capillary high voltage ±3 kV, sample solution flow rate 1.0 μ L/min. MeCN (special purity grade, water content < 0.03%, v/v, Cryochrom) and double distilled water were used to prepare solutions. TBA salts were purchased from Sigma-Aldrich with different purity: TBACN (95%), TBANO₃ (97%), TBAACO (97%), TBAF·H₂O (98%), TBACI (\geq 97%), TBABr (\geq 98%), TBAI (98%), TBAH₂PO₄ (\geq 99%), and TBAHSO₄ (\geq 99%).

2.2. Synthesis of the compounds

2.2.1. Synthesis of 2-amino-1-hydroxyanthracene-9,10-dione (3)

The synthesis was performed according to the published method [17]. A solution of 2-aminoanthraquinone (0.22 g, 1.0 mmol) and diethylamine (1 mL, 10 mmol) in 200 mL of benzene in a quartz ampoule was irradiated with light from a 125 W ultrahigh-pressure mercury lamp for 20 h with O₂ bubbling through the solution. The process was monitored by TLC. At the end of photolysis, the reaction mixture was evaporated to a volume of 5-10 mL, and then chromatographed on a column with SiO₂ $(40-63 \mu m)$ using benzene as the eluent. The dark red fraction was collected and evaporated to dryness in vacuo. The residue was airdried for 10 h to obtain compound **3** as a dark red powder (0.17 g, vield 72%): ¹H NMR (500 MHz, DMSO- d_6 , Fig. S1) δ : 12.86 (1H, s, OH), 8.17 (1H, dd, J = 7.6, 1.2 Hz, 5-H), 8.12 (1H, dd, J = 7.6, 1.2 Hz, 8-H), 7.88 (1H, td, *J* = 7.5, 1.5 Hz, 6-H), 7.83 (1H, td, *J* = 7.5, 1.5 Hz, 7-H), 7.59 (1H, d, J = 8.3 Hz, 4-H), 6.93 (1H, d, J = 8.3 Hz, 3-H), 6.45 (2H, brs, NH₂) ppm. Found: C, 70.48; H, 3.91; N, 5.71. Calc. for C₁₄H₉NO₃: C, 70.29; H, 3.77; N, 5.86%.

2.2.2. Synthesis of N-(1-hydroxy-9,10-dioxo-9,10dihydroanthracen-2-yl)benzamide (1a)

A mixture of compound **3** (0.24 g, 1.0 mmol) and benzovl chloride (0.2 g, 1.4 mmol) in 20 mL of toluene was refluxed for 1 h until the initial amino derivative disappeared (TLC monitoring). The reaction mixture was evaporated in vacuo to a volume of 2-3 mL, and diethyl ether was added. The precipitate formed was filtered off, washed with ether, and then chromatographed on a column with SiO₂ (40–63 μ m) using chloroform as the eluent. The main yellow fraction containing the target compound was collected and evaporated in vacuo. The residue was air-dried at 80 °C for 3 h to obtain compound **1a** as orange flakes (0.3 g, yield 87%). ¹H NMR (500 MHz, CDCl₃, Fig. S2) δ: 13.36 (1H, s, OH), 8.97 (1H, d, J = 8.4 Hz, 4-H), 8.88 (1H, brs, NH), 8.29-8.34 (2H, m, 5,8-H), 7.92-7.98 (3H, m, 2',6',3-H), 7.77-7.86 (2H, m, 6,7-H), 7.58-7.64 (1H, m, 4'-H), 7.52–7.58 (2H, m, 3',5'-H) ppm. ¹³C NMR (125 MHz, CDCl₃, Fig. S4) δ: 189.37, 181.44, 165.65, 151.14, 135.21, 134.29, 134.01, 133.64, 133.15, 132.65, 129.16, 127.75, 127.39, 127.05, 124.68, 121.20, 115.55 ppm. IR (KBr) $\nu_{\text{max}}/\text{cm}^{-1}$: 3440 (O-H); 3390 (N-H); 3065 (ar. C-H); 1688, 1658 (C=O); 1590 (ar. C=C). Found: C, 73.58; H, 3.98; N, 4.07. Calc. for C₂₁H₁₃NO₄: C, 73.46; H, 3.82; N, 4.08%. *m/z* (ESI-MS) $342.0782 ([M - H]^{-}).$

2.2.3. Synthesis of N-(9,10-dioxo-9,10-dihydroanthracen-2-yl) benzamide (1c)

The synthesis of compound **1c** was described for the first time in the article [18]. Acylation of 2-aminoanthraquinone (**2**) was performed according to the procedure described above for anthraquinone **3**. From 1.1 g of the starting **2**, 1.45 g (90%) of compound **1c** was isolated in the form of yellow flakes. ¹H NMR (500 MHz, CDCl₃, Fig. S6) δ : 8.47–8.52 (2H, m, 4-H, NH), 8.31–8.34 (1H, m, 5-H), 8.25–8.29 (2H, m, 1,8-H), 8.15 (1H, d, *J* = 8.8 Hz, 3-H), 7.89–7.93 (2H, m, 2',6'-H), 7.69–7.79 (2H, m, 6,7-H), 7.55–7.59 (1H, m, 4'-H), 7.47–7.52 (2H, m, 3',5'-H) ppm. Found: C, 77.36; H, 4.02; N, 4.20. Calc. for C₂₁H₁₃NO₃: C, 77.06; H, 3.98; N, 4.28%.

2.3. Spectrophotometry

The equilibrium reactions involving an anthraquinone dye and a TBA salt were studied by spectrophotometric titration (SPT). All SPT experiments were conducted in MeCN–H₂O (95:5, v/v) mixtures in 1 cm cells. The total concentration of dye **1a** or **1b** was maintained constant, and the total concentration of the TBA salt increased incrementally from zero. The equilibrium constants as well as the absorption spectra of pure species were determined by globally fitting the SPT data to an appropriate equilibrium reaction [19].

The cyanide anion detection limit was determined as follows: first, the absorption spectrum of **1a** in MeCN–H₂O (95:5, v/v) was recorded 10 times to estimate the standard deviation (SD) of the optical density at the absorption maximum (426 nm); then the optical density at the absorption peak of the product of the interaction of **1a** with TBACN (524 nm) was measured as a function of the TBACN concentration to calculate the slope (*S*) of the titration curve at the origin; the detection limit was calculated by the equation

Detection limit =
$$3SD/S$$
, (1)

2.3.1. Density functional theory (DFT) calculations

Geometry optimizations were performed with the Gaussian 16 program package [20] using the M06–2X functional [21] and the 6-31+G(d,p) basis set. The vibrational frequencies were calculated at the same level of theory to verify the nature of stationary points and to derive thermochemical quantities (a scale factor of 0.967 was used for harmonic frequencies). The SMD polarizable continuum model [22] was employed to simulate effects of MeCN as the experimental solvent. The Gibbs free energy in solution *G*(s) was calculated as follows:

$$G(\mathbf{s}) = E^{\mathrm{H-L}}(\mathbf{s}) + G_{\mathrm{T}}^{\mathrm{L-L}}(\mathbf{s})$$

where $E^{H-L}(s)$ – is the electronic energy derived from the single point M06–2X/6–311++G(2df,2p)/SMD(MeCN) calculation on the M06–2X/6-31+G(d,p)/SMD(MeCN) geometry, $G_T^{L-L}(s)$ is the thermal correction to the free energy, including the zero-point vibrational energy, calculated for the M06–2X/6-31+G(d,p)/SMD(MeCN) geometry.

The energies of vertical electronic transitions and the molecular orbitals involved were calculated using the time-dependent DFT (TDDFT) with the mPW2PLYP functional [23], the def2-TZVP(-f) basis set, and the SMD solvation model (MeCN). These calculations were done using the ORCA 4.1.0 program [24,25].

2.4. X-ray diffraction analysis

X-ray diffraction measurements were carried out on an Xcalibur diffractometer at 100 K using an EOS CCD detector and monochromatized MoK_α radiation ($\lambda = 0.71073$ Å). The determination and refinement of unit cell parameters were performed using the *CrysAlisPro* software [26]. The structure was solved by direct methods and refined against all *F* [2] data. All non-hydrogen atoms were refined with anisotropic thermal parameters; the positions of hydrogen atoms were obtained from difference Fourier syntheses and refined using the riding model. Calculations were performed using the SHELXTL software suite [27]. Selected crystallographic parameters and the refinement statistics are given in Table S1 (ESI). The X-ray crystal structure data for compound **1a** were deposited at the Cambridge Crystallographic Data Center under number CCDC 2070373.

3. Results and discussion

3.1. Synthesis

The anthraquinone **1a** was first obtained by the oxidation of 2benzoylaminoanthraquinone (**1c**) with air oxygen [28]. In this work, compound **1a** was synthesized in two stages (Scheme 1) from commercially available 2-aminoanthraquinone (**2**). At the first stage, photohydroxylation of amine **2** was performed in the presence of diethylamine and oxygen according to the published procedure [17] to obtain 2-amino-1-hydroxyanthraquinone (**3**). Next, compound **3** was acylated with benzoyl chloride by boiling in toluene to give anthraquinone **1a** with the total yield of 63% for the two stages. In this case, the by-product of acylation on the hydroxyl group was absent due to the strong hydrogen bond of the hydroxyl proton with the carbonyl oxygen atom in the *peri* position.

2-Benzoylaminoanthraquinone (**1c**) was prepared in a similar manner, excluding the photohydroxylation step.

3.2. X-ray diffraction study

Fig. 1 shows the crystal structure of **1a** (bond lengths and angles are summarized in Tables S1 and S2, ESI). All bond lengths and angles have standard values. In general, the molecule of **1a** is not planar; the dihedral angle between the anthraquinone and phenyl fragments is equal 48.4°. Unlike the unsubstituted anthraquinone molecule [29], the anthraquinone residue in **1a** is not fully planar: the dihedral angles between the central quinone ring and the side benzene ones are 4.1° and 4.8°. The observed orientation of the hydroxyl group is due to strong intramolecular hydrogen bonding to the O(1) atom: the length of the O(3)H···O(1) hydrogen bond is 1.75 Å, the angle at the hydrogen atom is 141.5°, and the distance between O(3) and O(1) is 2.59 Å.

Compound **1a** crystallizes in the monoclinic space group $P2_1/c$. Fig. 2 shows the crystal packing of **1a**. The molecules of **1a** are packed in stacks; π - π stacking interactions are observed both between anthraquinone residues and between phenyl rings (interplanar distances are 3.41 and 3.35 Å, respectively). The crystal structure of **1a** is stabilized by π - π stacking interactions, the weak hydrogen bonds between hydroxyl groups of adjacent molecules, and the O(carbonyl)····HC hydrogen bonds (Fig. 2).

3.3. Spectrophotometry

To study the anionic sensory properties of anthraquinones **1a–c**, nine tetrabutylammonium (TBA) salts (counterions CN⁻, F⁻, AcO⁻, H₂PO₄⁻, Cl⁻, Br⁻, I⁻, HSO₄⁻, and NO₃⁻) were added to solutions of the anthraquinones in a MeCN–H₂O mixture (95:5, v/v).

The addition of tetrabutylammonium cyanide (TBACN) to a solution of the anthraquinone dye **1a** led to a decrease in the intensity of the long-wavelength absorption band ($\lambda_{max} = 426$ nm) of the dye and the appearance of a new band with $\lambda_{max} = 524$ nm (Fig. 3*a*). The two isosbestic points observed in the spectrophotometric titration (SPT) spectra indicate the formation of a single colored species.

In the case of 1-hydroxyanthraquinone (**1b**), the addition of TBACN resulted in similar spectral changes (Fig. 3*b*), *viz.*, the disappearance of the absorption band peaked at 401 nm and the appearance of a new long-wavelength band peaked at 509 nm. The addition of TBACN to a solution of anthraquinone **1c**, which differs from **1a** only by the absence of a hydroxyl group, in a 10-fold excess caused no discernible spectral changes. These facts suggest that the TBACN-induced spectral changes observed with dye **1a** are due to the interaction of CN⁻ with the hydroxyl group at position 1 of the anthraquinone core, rather than to the addition of CN⁻ at the C=O double bond of the benzoylamino group. It is most likely that the



Scheme 1. Synthesis of anthraquinone 1a.



Fig. 1. Crystal structure of 1a and atom numbering.

hydroxyl group in compounds **1a** and **1b** is deprotonated in the presence of CN^- due to the high basicity of the cyanide anion, which leads to the formation of deeply colored anionic forms of **1a** and **1b**. The cyanide anion detection limit for chemosensor **1a** in MeCN-H₂O (95:5, v/v) was determined using the expression (1) to be 0.22 μ M.

Solutions of compound **1a** showed relatively small color responses to TBAF and TBAAcO salts (Fig. 4). No color responses were observed in the case of the TBA salts with counterions $H_2PO_4^-$, Cl^- , Br^- , l^- , HSO_4^- , and NO_3^- .

The addition of 10 equivalents of any of the above TBA salts to a solution of compound **1c** caused no discernible changes in the so-





Fig. 2. Crystal packing of 1a: (*a*) stacks (H atoms and intermolecular contacts are omitted for clarity), (*b*) the projection onto the *bc* plane (cyan dash lines show the intermolecular contacts).



Fig. 3. Absorption spectra of the systems (a) **1a**–TBACN and (b) **1b**–TBACN in MeCN–H₂O (95:5, v/v) in a 1 cm cell: (a) 4.8×10^{-5} M **1a** and $0-3.3 \times 10^{-4}$ M TBACN, (b) 9.2×10^{-5} M **1b** and 0-0.017 M TBACN. The red curves show the spectra of the anionic forms of **1a** and **1b**, as derived from fitting the SPT data to equilibrium (3), see below.



Fig. 4. (a) Color responses of a solution of anthraquinone **1a** in MeCN–H₂O (95:5, v/v) to various TBA salts (the salts were added in two equivalents); (b) the corresponding absorption spectra.

lution color (Fig. S7, ESI). In the case of unsubstituted 1hydroxyanthraquinone (compound **1b**), discernible color changes were observed only when TBACN salt was added (Fig. S8, ESI).

3.4. Mass spectrometry

Fig. 5 shows the average electrospray ionization (ESI) mass spectra of equimolar mixtures of TBACN with anthraquinones **1a** and **1b** in MeCN in the negative-ion mode.

The ESI mass spectra were acquired using an Exactive Orbitrap mass spectrometer (ThermoFisher Scientific, Germany). The working resolution of the mass spectrometer in the reported studies was 10000 (FWHM). The ratio error of the *m/z* values measurement was better than $5 \cdot 10^{-6}$. Analysis of the isotopic structure of the registered ion peaks and the accurate measurement of the ion masses allowed identifying all the main ions that were detected. The intense signal at m/z = 141.9390 was assigned to the [Zn(CN)₃]⁻ ions. The signal from these ions is a result of a design feature of the electrospray ion source homemade from brass. For

both hydroxyanthraquinones **1a** and **1b**, the mass spectra (Fig. 5) contain intense signals of anionic forms. At that, no peaks of possible adducts with cyanide anions were observed. The positive-ion mass spectra of these equimolar mixtures were dominated by the signal from the TBA⁺ ion (Figs S9 and S10, ESI MS).

3.5. Quantum-chemical calculations

To determine the product of the interaction of CN^- with anthraquinone **1a**, we carried out a quantum chemical DFT study of a few possible structures, including the product of the addition of CN^- to the carbon atom of the carbonyl group at position 9 of the anthraquinone core, the product of the addition of CN^- to the carbonyl carbon atom of the NHCOPh group, the anionic form of **1a** and its associate with HCN (Fig. 6).

Table S3 (ESI) shows the calculated free energies *G*(s) for structures Adduct-1 (Fig. 6*a*), Adduct-2 (Fig. 6*b*), and Anion-HCN (Fig. 6*c*). To compare the stability of associate Anion-H₂O (Fig. 6*d*) with those of the above structures, the *G*(s) value calculated for this associate was corrected by subtracting the free energy of H₂O and adding the free energy of HCN (Table S3, ESI). According to calculations, the relative *G*(s) value increases in the following order: Anion-HCN < Adduct-1 (+0.2 kcal mol⁻¹) < [Anion-H₂O + HCN - H₂O] (+1.1 kcal mol⁻¹) \ll Adduct-2 (+15.4 kcal mol⁻¹). These data imply that the formation of Adduct-2 is extremely unlikely. The other three systems are close to each other in energy; therefore, further selection was made on the basis of TDDFT calculations (see the Experimental section). The results of these calculations are presented in Table 1.

The S_0 – S_1 transition wavelength calculated for Adduct-1 deviates strongly from that observed for the product of the interaction of anthraquinone **1a** with CN⁻. For the **1a** anionic form, its hydrate, and its associate with HCN, the deviations are within the calculation accuracy.

3.6. Equilibrium constant measurements

The SPT, mass spectrometry, and quantum chemical calculation data clearly indicate that the interaction of TBACN with hydroxyanthraquinone **1b** and its benzoylamino derivative **1a** leads to deprotonation of the hydroxyl group of the anthraquinone. The formation of the anionic form can be represented with the following equilibrium:

$$HA + CN^{-} \stackrel{KA}{\rightleftharpoons} {}^{K_{A}}A^{-} + HCN \tag{2}$$

where HA is the hydroxyanthraquinone, A^- is its phenolate form, and K_A is the reaction equilibrium constant.



Fig. 5. The average ESI mass spectra (negative ions) of equimolar mixtures of TBACN (1×10^{-4} M) with anthraquinones (a) 1a and (b) 1b in MeCN.



Fig. 6. Geometries of possible products of the interaction of CN⁻ with anthraquinone 1a, as derived from the M06–2X/6-31+G(d,p)/SMD(MeCN) calculations.

Table 1

TDDFT-calculated wavelengths of the S_0-S_1 electronic transition, λ_{calc} (nm), for anthraquinone **1a** and possible products of its interaction with $CN^{-,a}$

Compound	λ_{calc}	λ_{\max}^{b}	$\Delta \lambda^{c}$
1a	425	426	1
Adduct-1	463	524	61
Anion•HCN	509	524	15
Anion	537	524	13
Anion•H ₂ O	519	524	5

^aThe TDDFT calculations were performed using the mPW2PLYP functional, the def2-TZVP(-f) basis set, and the SMD solvation model (MeCN).

 b λ_{max} (nm) is the peak position of the S₀–S₁ band in the experimental spectrum for anthraquinone **1a** and the product of its interaction with CN⁻.

 $^{c} \Delta \lambda = |\lambda_{max} - \lambda_{calc}|.$

When using the equilibrium (2), the parameterized matrix modeling [19] of the SPT data obtained for **1a** and **1b** (Fig. 3) led to rather large discrepancies between the experimental and model absorption spectra (Fig. S11*a*). It was found that the SPT data are much better approximated (Fig. S11*b*) when using the simple complexation model (3):

$$HA + CN^{-} \stackrel{K}{\rightleftharpoons} [A \cdot HCN]^{-}$$
(3)

where $[A \cdot HCN]^-$ is the associate of the hydroxyanthraquinone anion with prussic acid, *K* is the stability constant of the associate. The formation of $[A \cdot HCN]^-$ is consistent with the data of DFT calculations (Tables 1 and S3). Table 2 shows the spectral properties of

 Table 2

 Stability constants and absorption properties of associates of compounds 1a-c with different anions.^a

Compound	logK ^a	λ_{max}	$\varepsilon_{max} imes 10^{-3}$	Δλ
1a		426	9.04	
[1a ·CN] ⁻	4.88	524	13.0	+98
[1a ∙F] [_]	2.62	526	11.6	+100
[1a •AcO] ⁻	<2	526	12	+100
1b		401	5.28	
[1 b ·CN] ⁻	~2	509	5.7	+108
1c		371	12.1	

^a In MeCN–H₂O (95:5, v/v), the *K* values (M⁻¹) are measured to within about ±20% (except for [**1a**-AcO]⁻ and [**1b**-CN]⁻); λ_{max} is the position of the S₀–S₁ absorption band maximum; ε_{max} is the molar absorptivity at λ_{max} ; $\Delta\lambda$ is the complexation-induced shift of λ_{max} .

anthraquinones **1a**–**c** and their associates; the stability constants for the latter are also given.

For systems **1a**–TBAACO and **1b**–TBACN, the accuracies of measuring the stability constants and ε_{max} of associates are relatively low, since it was not possible to achieve a high degree of complexation. The data in Table 2 show that the associate [**1b**·CN]⁻ is significantly less stable than the associate [**1a**·CN]⁻ (logK values are ~2 and 4.88, respectively). This difference is attributable to the fact that the anionic form of **1a** is stabilized due to the electron-withdrawing nature of the NHCOPh group and due to the



Fig. 7. Changes in the ¹H NMR spectrum of anthraquinone **1a** (1.9×10^{-3} M) in CD₃CN–DMSO-*d*₆ (9:1, v/v) upon addition of different amounts of TBACN; the TBACN concentrations are (1) 0, (2) 4.0 × 10⁻⁴, (3) 8.0 × 10⁻⁴, (4) 1.2 × 10⁻³, (5) 1.6 × 10⁻³, (6) 2.0 × 10⁻³, (7) 2.8 × 10⁻³, and (8) 4.8 × 10⁻³ M.

hydrogen bonding between the amide hydrogen atom and the oxygen atom of the ionized hydroxyl group (the main factor is the hydrogen bonding).

3.7. NMR spectroscopy

Fig. 7 shows the ¹H NMR spectra of hydroxyanthraquinone **1a** in CD₃CN–DMSO- d_6 (9:1, v/v), measured at different concentrations of added TBACN salt. The addition of TBACN results in a significant downfield shift (by 1.64 ppm) of the NH proton signal and significant upfield shifts of the 3-H and 4-H signals (up to 0.74 ppm). The hydroxyl proton signal becomes indistinguishable after the first addition of the salt (4.0×10^{-4} M).

It has been previously reported [16] that the interaction of the trifluoroacetamide anthraguinone derivative **1d** (Chart 1) with TBACN led to the disappearance of the NH proton signal and to strong upfield shifts of the signals of almost all aromatic protons. These changes were explained by the addition of CN⁻ at the double carbonyl bond of the NHC=O unit. The shifts of the proton signals of anthraquinone **1a**, observed after the addition of TBACN cannot be explained by the formation of a similar adduct (Adduct-2, Fig. 6), since the positions of the signals of the phenyl protons of the NHCOPh group remain practically unchanged. The most likely explanation, as mentioned above, is the deprotonation of the hydroxyl group of **1a**. The large upfield shift and strong broadening of the NH proton signal of **1a** in the presence of TBACN are probably due to the exchange interaction with the deprotonated oxygen atom at position 1. The absence of a proton signal from HCN after the addition of excess TBACN to a solution of 1a (Figs S13 and S14, ESI) counts in favor of the formation of associate [1a·CN]⁻ rather than free anionic form of **1a** and free HCN (it is known [30] that pure HCN in the liquid phase gives a proton signal at 3.60 ppm).

Fig. 8 shows the chemical shift changes, $\Delta\delta$, for the NH and 4-H protons of **1a** as functions of the ratio of the concentrations of TBACN and **1a** in CD₃CN–DMSO- d_6 (9:1, v/v). These data were used to estimate the stability constant *K* (eq (3)) by the method of global analysis of NMR titration data [31]. The value of log*K* was calculated to be 4.72, which is close to that obtained using the SPT method (Table 2).

3.8. Practical application

The potential usefulness and practical applicability of receptor **1a** for the cyanide anion detection in aqueous media were tested by





Fig. 9. Color scale for determining CN⁻ using paper test strips.

making test strips. The test strips were prepared by immersing filter papers into DMSO/H₂O (8:2, v/v) solution of **1a** (1×10^{-3} M) for 10 min and then drying in air. Aqueous solutions containing cyanide in the concentration range from 10^{-8} to 1 M were used to construct the color scale of the determined ion. When the test strips were immersed in these solutions, the color of the strips instantly changed from yellow to purple (Fig. 9). This demonstrates that the chemosensor **1a** is capable to rapidly detect cyanide anion in aqueous environment. Therefore, we believe that the test strips could act as a convenient and efficient CN⁻ test kit.

4. Conclusions

New easy-to-make chemoreceptor to function as a selective chromogenic probe for cyanide ions in water-containing solutions was developed. The interaction of the studied 2-benzoylamino-1hydroxyanthraquinone (1a) with cyanide results in the appearance of a new long-wavelength absorption band and thereby in a contrasting change in the solution color from yellow to red-purple. The anion-induced spectral changes are caused by deprotonation of the hydroxyl group of anthraquinone **1a**. The logarithm of the stability constant of the resulting associate [1a·CN]⁻ is 4.88 in MeCN-H₂O (95:5, v/v). It was found that the benzoylamino group at position 2 of dye **1a** stabilizes the anionic form of the dye due to the hydrogen bonding between the amide hydrogen atom and the oxygen atom of the ionized hydroxyl group. The detection limit for cvanide anion was calculated to be 0.22 uM, which is much lower than the standard limit set by the World Health Organization. Experiments with test strips containing anthraquinone 1a demonstrated the possibility of using this compound as a chemoreceptor in materials for detecting highly toxic cyanide ions with the naked eye.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the Russian Foundation for Basic Research (project No. 18-43-860005) and by the Ministry of Science and Higher Education of the Russian Federation with respect to the X-ray diffraction analysis (State Assignment No. AAAA-A19-119092390076-7), with respect to the mass spectrometry analysis (State Assignment No. AAAA-A18-118112690060-9) and the quantum chemical calculations (State Assignment No. AAAA-A19-119070790003-7). The work was performed using the equipment of the Multi-User Analytical Center of IPCP RAS.

Appendix A. Supplementary data

Supplementary data to this article can be found online at

https://doi.org/10.1016/j.tet.2021.132312.

References

- M.H. Chua, K.W. Shah, H. Zhou, J. Xu, Recent advances in aggregation-induced emission chemosensors for anion sensing, Molecules 24 (15) (2019) 2711–2756, https://doi.org/10.3390/molecules24152711.
- [2] P.A. Gale, C. Caltagirone, Fluorescent and colorimetric sensors for anionic species, Coord. Chem. Rev. 354 (2018) 2–27, https://doi.org/10.1016/ j.ccr.2017.05.003.
- [3] N. Kaur, G. Kaur, U.A. Fegade, A. Singh, S.K. Sahoo, A.S. Kuwar, et al., Anion sensing with chemosensors having multiple –NH recognition units, TrAC Trends Anal. Chem. (Reference Ed.) 95 (2017) 86–109, https://doi.org/ 10.1016/j.trac.2017.08.003.
- [4] N.A. Itsikson, Y.Y. Morzherin, A.I. Matern, O.N. Chupakhin, Receptors for anions, Russ. Chem. Rev. 77 (9) (2008) 751–764, https://doi.org/10.1070/ RC2008v077n09ABEH003762.
- [5] L. Yang, X. Li, J. Yang, Y. Qu, J. Hua, Colorimetric and ratiometric near-infrared fluorescent cyanide chemodosimeter based on phenazine derivatives, ACS Appl. Mater. Interfaces 5 (4) (2013) 1317–1326, https://doi.org/10.1021/ am303152w.
- [6] P.A. Lieberzeit, F.L. Dickert, Chemosensors in environmental monitoring: challenges in ruggedness and selectivity, Anal. Bioanal. Chem. 393 (2) (2009) 467–472, https://doi.org/10.1007/s00216-008-2464-3.
- [7] R. Koenig, Environmental disasters: wildlife deaths are a grim wake-up call in Eastern Europe, Science 287 (5459) (2000) 1737–1738, https://doi.org/ 10.1126/science.287.5459.1737.
- [8] D. Udhayakumari, Chromogenic and fluorogenic chemosensors for lethal cyanide ion. A comprehensive review of the year 2016, Sens. Actuators, B 259 (2018) 1022–1057, https://doi.org/10.1016/j.snb.2017.12.006.
- [9] F. Wang, L. Wang, X. Chen, J. Yoon, Recent progress in the development of fluorometric and colorimetric chemosensors for detection of cyanide ions, Chem. Soc. Rev. 43 (13) (2014) 4312–4324, https://doi.org/10.1039/ C4CS00008K.
- [10] P.B. Pati, Organic chemodosimeter for cyanide: a nucleophilic approach, Sens. Actuators, B 222 (2016) 374–390, https://doi.org/10.1016/j.snb.2015.08.044.
- [11] B. Wang, E.V. Anslyn, Chemosensors: Principles, Strategies, and Applications, Wiley, Hoboken, N.J., 2011.
- [12] P. Rajalakshmi, P. Jayasudha, S. Ciattini, L. Chelazzi, K.P. Elango, Crystallographic evidence for resonance assisted H-Bonding effect in selective colorimetric detection of cyanide by arylaminonaphthoquinones, J. Mol. Struct. 1195 (2019) 259–268, https://doi.org/10.1016/j.molstruc.2019.05.124.
- [13] Q. Niu, T. Sun, T. Li, Z. Guo, H. Pang, Highly sensitive and selective colorimetric/fluorescent probe with aggregation induced emission characteristics for multiple targets of copper, zinc and cyanide ions sensing and its practical application in water and food samples, Sens. Actuators, B 266 (2018) 730–743, https://doi.org/10.1016/j.snb.2018.03.089.
- [14] H. Yao, J. Wang, S.-S. Song, Y.-Q. Fan, X.-W. Guan, Q. Zhou, et al., A novel supramolecular AIE gel acts as a multi-analyte sensor array, New J. Chem. 42 (2018) 18059–18065, https://doi.org/10.1039/C8NJ04160A.
- [15] R. Saini, N. Kaur, S. Kumar, Quinones based molecular receptors for

recognition of anions and metal ions, Tetrahedron 70 (29) (2014) 4285–4307, https://doi.org/10.1016/j.tet.2014.04.058.

- [16] H.-T. Niu, D. Su, X. Jiang, W. Yang, Zh Yin, J. He, et al., A simple yet highly selective colorimetric sensor for cyanide anion in an aqueous environment, Org. Biomol. Chem. 6 (17) (2008) 3038–3040, https://doi.org/10.1039/ b808589g.
- [17] K. Yoshida, M. Hikasa, K. Ishii, H. Kadota, Y. Yamashita, The selective introduction of hydroxy and alkylamino groups into the anthraquinone nucleus was achieved by the photochemical reaction of some aminoanthraquinones and their N-acylated derivatives with alkylamines under aerobic conditions, J. Chem. Soc. Chem. Commun. 10 (1986) 758–759, https://doi.org/10.1039/ C39860000758.
- [18] M.A. Il'inskii, A.A. Zaikin, Dynamics of acid saponification of benzoyl derivatives of anthraguinones, Zh. Obshch. Khim. 4 (1934) 1294–1302.
- [19] E.N. Ushakov, S.P. Gromov, O.A. Fedorova, YuV. Pershina, M.V. Alfimov, et al., Sandwich-type complexes of alkaline-earth metal cations with a bisstyryl dye containing two crown ether units, J. Phys. Chem. 103 (50) (1999) 11188–11193, https://doi.org/10.1021/jp9929420.
- [20] Gaussian 16, Revision A.03, Gaussian, Inc., Wallingford CT, 2016.
- [21] Y. Zhao, D.G. Truhlar, The M06 suite of density functionals for main group thermochemistry, thermochemical kinetics, noncovalent interactions, excited states, and transition elements: two new functionals and systematic testing of four M06-class functionals and 12 other functionals, Theor Chem Acc 120 (2008) 215–241, https://doi.org/10.1007/s00214-007-0310-x.
- [22] A.V. Marenich, C.J. Cramer, D.G. Truhlar, Universal solvation model based on solute electron density and on a continuum model of the solvent defined by the bulk dielectric constant and atomic surface tensions, J. Phys. Chem. B 113 (18) (2009) 6378–6396, https://doi.org/10.1021/jp810292n.
- [23] T. Schwabe, S. Grimme, Towards chemical accuracy for the thermodynamics of large molecules: new hybrid density functionals including non-local correlation effects, Phys. Chem. Chem. Phys. 8 (38) (2006) 4398–4401, https:// doi.org/10.1039/B608478H.
- [24] F. Neese, The ORCA program system, Wiley Interdiscip Rev: Comput Mol Sci. 2 (1) (2012) 73-78, https://doi.org/10.1002/wcms.81.
 [25] F. Neese, Software update: the ORCA program system, version 4.0, Wiley
- [25] F. Neese, Software update: the ORCA program system, version 4.0, Wiley Interdiscip Rev: Comput Mol Sci 8 (1) (2017) e1327, https://doi.org/10.1002/ wcms.1327.
- [26] CrysAlisPro, Version 171.36.20, Agilent Technologies UK Ltd, Yarnton, Oxfordshire, England, 2011.
- [27] SHELXTL, Version 6.14, Bruker AXS, Madison, Wisconsin, USA, 2000.
- [28] Denisov VYa, N.A. Pirogova, Photohydroxylation of 2acylaminoanthraquinones, Zh. Org. Khim. 18 (11) (1982) 2397–2398.
- [29] B.V.R. Murty, Refinement of the structure of anthraquinone, Zeitschrift fur Kristallographie 113 (1960) 445–465, https://doi.org/10.1524/ ZKRI.1960.113.1-6.445.
- [30] G. Binsch, J.D. Roberts, Nitrogen-15 magnetic resonance spectroscopy. Coupling constants in hydrogen cyanide, J. Phys. Chem. 72 (12) (1968) 4310–4311, https://doi.org/10.1021/j100858a064.
- [31] T.P. Martyanov, L.S. Klimenko, V.I. Kozlovskiy, E.N. Ushakov, Tautomeric chromoionophores derived from 1-aryloxyanthraquinones and 4'-aminobenzo-15-crown-5 ether: sandwich complex formation enhanced by interchromophoric interactions, Tetrahedron 73 (6) (2017) 681–691.