

Simple Electrooptical Sensors for Inorganic Anions

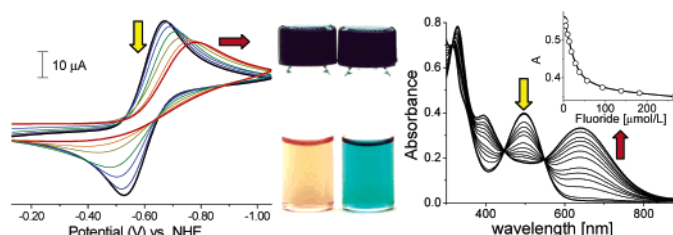
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ABSTRACT



Electrooptical sensors consisting of a conjugated chromophore undergoing a change in color and a redox-active moiety such as quinone fused to the chromophore were synthesized. Strong changes in colorimetric and electrochemical properties were observed in the presence of inorganic anions. A unique anion-specific response was observed for fluoride, pyrophosphate, and acetate. DFT (B3LYP/6-31G*) calculations performed for both “on/off” states of a sensor-fluoride model are in good agreement with the observed electrochemical and spectroscopic data.

The ubiquity of anions and their importance as agricultural fertilizers and industrial raw materials necessitates the development of highly sensitive anion sensors.¹ Here, materials capable of reversible anion-induced changes in color are particularly attractive² because they may be used as dip-stick sensors. Unfortunately, few colorimetric anion sensors are able to differentiate selectively between anionic substrates of similar basicity and surface charge density.^{2b,c} An additional problem is the compatibility of most of the anion sensors with water and electrolytes. To limit potentially ambiguous results, we synthesized sensors that utilize independent, optical, and electrochemical output signals. Although known, such materials are still rare and their synthesis is often complex.^{2,3}

The potential disadvantage of anion sensors utilizing hydrogen bonding in water may be circumvented by using

optically transparent polymeric anion exchange films as analyte preconcentration layers into which analyte ions partition.⁴ Such materials capable of stripping the bulk of the water and/or accompanying electrolytes off the target analyte would be ideal host materials for embedding sensor moieties generating the spectroelectrochemical response and may provide a future generation of highly reliable anion sensors. This, however, requires viable sensor molecules that operate in water/electrolyte matrices.

Here we report on sensors **1–3** (Figure 1) comprising a chromophore capable of undergoing an intensive change in color and a redox-active quinone moiety⁵ to generate strong colorimetric and electrochemical signals. The quinone moiety is directly fused to the chromophore and the hydrogen bond donors prone to bond polarization and partial charge transfer

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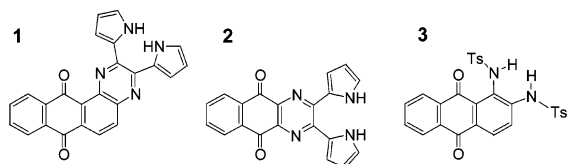
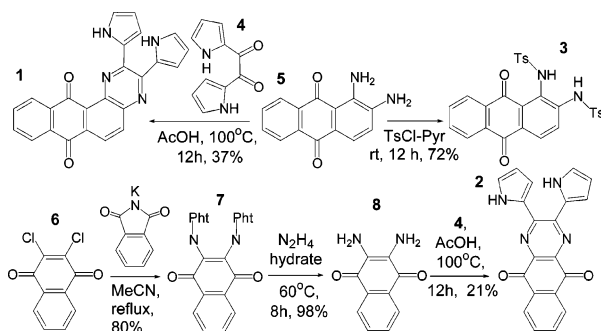


Figure 1. Structures of sensors **1–3** with integrated chromophore, redox-active moieties, and hydrogen bond donors.

due to hydrogen bonding to the anion. Our proof-of-principle experiments were performed using the sensors **1–3**.

Sensors **1** and **2** utilize the 2,3-dipyrrolylquinoxaline (DPQ)-like moiety recently rediscovered by Sessler as a potent anion binder.⁶ Compounds **1** and **2** were prepared (Scheme 1) by condensation of dipyrrolylethane-1,2-dione

Scheme 1. Synthesis of Sensors **1**, **2**, and **3**



4^{6b} with 1,2-diaminoanthraquinone **5** and 2,3-diamino[1,4]-naphthoquinone **8**,⁷ respectively. To prove that this design is general, we prepared sensor **3** with sulfonamide moieties described previously by Crabtree and Kavallieratos.⁸

Unfortunately, condensation of dione **4** with tetraamino-1,4-benzoquinone **10** (Scheme 2) yielded only traces of product **11** and copious amounts of polymer.⁹ Similarly, the mild conditions used to prepare 2,3,6,7-tetramethyl-1,4,5,8-tetraaza-9,10-anthraquinone¹⁰ did not give **11** in good yield (~2%), and the synthesis of **11** was not pursued further.

(5) (a) The first theses of this work were published as early as 2001; see: Anzenbacher, P., Jr.; Karpov, G. V.; Jursíková, K. Anion sensors with dual mode of detection. Abstracts of Papers, 222nd ACS National Meeting, Chicago, IL, 2001; ORGN-065. Later we became aware that our sensor **1** was also described in (b) Ghosh, T.; Maiya, B. G.; Wong, M. W. *J. Phys. Chem. A* **2004**, *108*, 11249. This paper describes the properties of sensor **1**. Unfortunately, the reported results differ significantly from our observations. There, sensor **1** displays an anodic shift in the presence of anions, which also contradicts the general trends proposed in Beer, P. D.; Gale, P. A.; Chen, G. Z. *J. Chem. Soc., Dalton. Trans.* **1999**, *12*, 1897.

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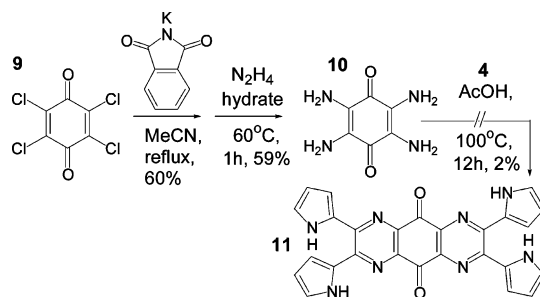
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Scheme 2. Synthesis of Sensor **11**



Visual inspection of solutions of sensors **1–3** (25 μ M in MeCN with 0.5% water) before and after addition of anion salts¹¹ showed a dramatic change in color in the case of fluoride, cyanide, acetate, and pyrophosphate ($\text{HP}_2\text{O}_7^{3-}$, PP^{3-}) suggesting strong binding, whereas the addition of dihydrogenphosphate (H_2PO_4^- , H_2P^-), benzoate, or chloride did not result in appreciable change in color (Figure 2). We

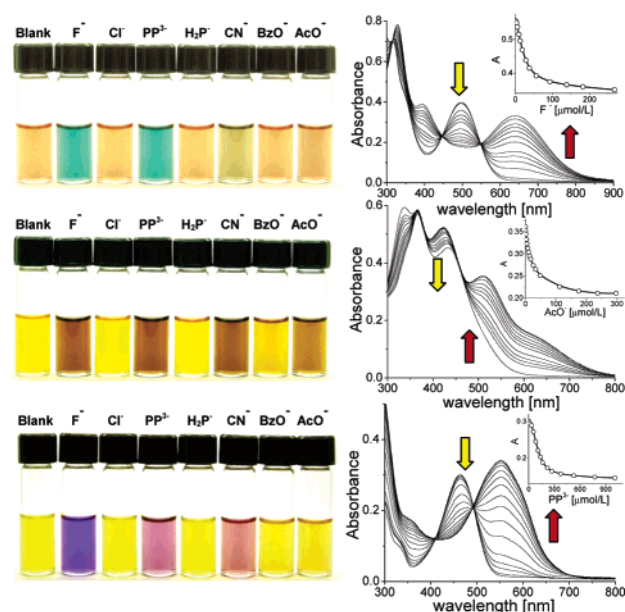


Figure 2. (Left panel) Solutions of sensors **1–3** (25 μ M in MeCN) in the presence of anions (50 equiv). (Right panel) Examples of UV-vis spectra of sensors **1–3** (**1**/ F^- , **2**/ AcO^- , **3**/ $\text{HP}_2\text{O}_7^{3-}$).

believe that this is due to a difference in sizes of binding sites (**1**, **2** vs **3**), as well as the direct result of acidity of protons involved in hydrogen bonding.

Quantitative measurements of anion affinity were performed by monitoring the changes in the UV-vis spectra of sensors **1–3** upon addition of an anion. The titrations were

(11) Hydrated tetrabutylammonium (TBA) salts of the anions were used in this study: fluoride ($\cdot 6\text{H}_2\text{O}$), chloride, phosphate ($\cdot 2\text{H}_2\text{O}$), and pyrophosphate ($\cdot 2\text{H}_2\text{O}$). The degree of hydration was estimated from elemental analyses. The supporting electrolyte was TBAClO_4 .

performed in MeCN both with and without the presence of supporting electrolyte (0.1 M TBAClO₄) (Table 1). Interestingly, the presence of the supporting electrolyte does not seem to affect significantly the receptor-anion affinity.

Table 1. Affinity Constants (K_a)^a for Compounds **1**, **2**, and **3** (M⁻¹) and Anionic Substrates in MeCN (25 μ M, 0.5% water at 22 °C)¹²

| anion | sensor 1 | sensor 2 | sensor 3 |
|----------------------------------------------|----------|----------|------------------|
| F ⁻ | 482 200 | 150 700 | >10 ⁶ |
| CN ⁻ | 6 630 | 16 800 | 11 900 |
| HP ₂ O ₇ ³⁻ | 316 000 | 626 000 | 1 428 |
| AcO ⁻ | 1 200 | 3 800 | <100 |
| H ₂ PO ₄ ⁻ | <100 | 525 | 220 |
| PhCO ₂ ⁻ | 100 | 400 | <50 |
| Cl ⁻ | <50 | <50 | <50 |

^a The binding constant were calculated with error lower than 15%.

To obtain the second “validating” signal output, the anion binding by sensors **1–3** was also investigated by cyclic (CV) and square-wave voltammetry (SWV).¹³ Both methods confirm that the anion binding is accompanied by an anion-specific change in redox potential as well as by decrease in current, a behavior attributed to the formation of the sensor–anion complex with a lower diffusion coefficient.¹³ Also, reduction waves of **1–3** show cathodic shifts due to the fact that the electron-rich sensor–anion complex is difficult to reduce. Figure 3 shows an example of the SWV of **1** titrated

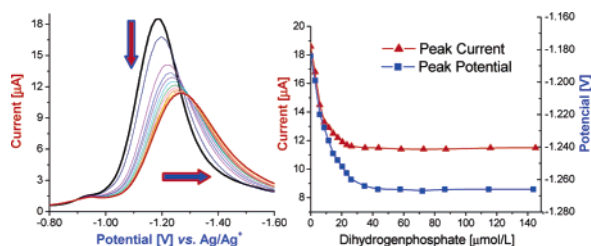


Figure 3. Changes in redox properties of **1** (50 μ M) upon addition of H₂PO₄⁻ observed by SWV (frequency = 15 Hz, increment = 0.004 V; 0.1 M TBAClO₄).

by H₂PO₄⁻. The changes in current or potential may be used to calculate binding constants.

Inspection of the data in Tables 1 and 2 reveals that the SWV titrations show measurable changes in peak current and reduction potential even in the case of anions that induce only a weak color change insufficient for reliable determination by absorption spectroscopy (e.g., H₂PO₄⁻).

The binding isotherms obtained from titration experiments carried out by UV–vis spectroscopy ($\Delta A = f_{[anion]}$) and

Table 2. Changes in Color and Current at Saturation in Sensors **1–3** in the Presence of Anions in MeCN (25 μ M, 0.5% water, 22 °C)^a

| | sensor 1 | | | sensor 2 | | | sensor 3 | | |
|----------------------------------------------|------------------------------|-------------------------------|-------------------------|------------------------------|-------------------------------|-------------------------|------------------------------|-------------------------------|-------------------------|
| | color ^b change | •I _s (μ A) | •E _p (mV) | color ^b change | •I _s (μ A) | •E _p (mV) | color ^b change | •I _s (μ A) | •E _p (mV) |
| F ⁻ | ●●● | ND ^c | 100 ^d | ●●● | 3.6 | 58 | ●●● | 0.9 | <5 |
| HP ₂ O ₇ ³⁻ | ●●○ | 3.7 | 84 | ●●● | 1.8 | 26 | ●●○ | 2.2 | 70 |
| H ₂ PO ₄ ⁻ | ○○○ | 7.1 | 82 | ○○○ | 3.8 | 53 | ○○○ | 2.0 | 121 |
| Cl ⁻ | ○○○ | 1.3 | <2 | ○○○ | 0.6 | <2 | ○○○ | 0.2 | <2 |
| AcO ⁻ | ●●○ | 5.6 | 34 | ●●○ | 12.9 | 47 | ●●○ | ND ^e | ND ^e |
| PhCO ₂ ⁻ | ●○○ | 1.5 | ~2 | ●○○ | 4.9 | 40 | ○○○ | ND ^e | ND ^e |

^a SWV (frequency = 15 Hz, increment = 4 mV, amplitude = 25 mV; 0.1 M TBAClO₄). Pt wire and Ag/Ag⁺ reference electrodes were used. The ferrocene/ferrocenium couple was determined to be +0.121. ^b ●●● indicates strong color change; ○○○ indicates no color change (determined as naked-eye observation). ^c The data suggest passivation of the electrode. ^d The data were obtained from the CV titration. ^e Partial decomposition of acetate coincides with reduction of sensor **3**.

square-wave voltammetry ($\Delta I = f_{[anion]}$) showed remarkable similarity and also yielded similar affinity constants (within the 15% error margin). For example, the affinity constant for sensor **2** and F⁻ by UV–vis and SWV was 28,300 and 33,400 M⁻¹, respectively (Figure 4).

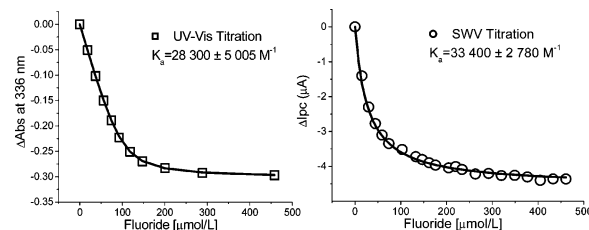


Figure 4. Examples of binding isotherms for **2** titrated with TBAF obtained from UV–vis and SWV measurements, both in MeCN/TBAClO₄.

Although the agreement in the electrochemical and spectrophotometric titration suggests that both types of changes originate from sensor–anion association, the data in Tables 1 and 2 reveal that the magnitude of the association constant does not necessarily correspond to the actual magnitude of anion-induced changes in current and reduction potential. For example, the magnitude in changes of the redox properties in **1–3** recorded for H₂PO₄⁻ matches the magnitude of changes in electrical properties recorded for F⁻. However, the affinity constants calculated from absorption spectra for F⁻ are higher than for H₂PO₄⁻. The same behavior was also reported for pyrrole–ferrocene systems.¹⁴ The phenomena that raise this disparity are still not entirely clear.^{14c}

Because most anionic analytes are administered predominantly as aqueous solutions, we have investigated the sensing

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process with anions added as a solution in water (25 mM). Here, the sensing process is rendered more complex due to multiple equilibria including hydration:



Given the time scale of the voltammetric experiments and the fast and reversible nature of the association/hydration processes, the ternary species composed of sensor, anion, and water, i.e., eqs 3, 4, and 5, would appear as one (eqs 3–5). From the above equilibria proposed for sensor **1** we should observe three different redox-active species in the voltammogram: free sensor, hydrated sensor (eq 1), and hydrated anion–sensor complex (eqs 3–5). Furthermore, we assume that in order for the hydration process to be energetically favorable, the hydrated sensor–anion complex (eqs 3–5) would show a lower reduction potential compared to the nonhydrated anion–sensor complex. Indeed, the SWV traces show three peaks as expected (Figure 5).

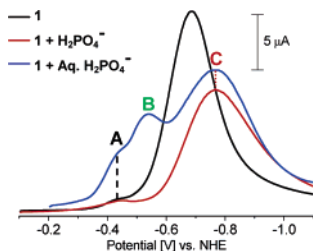


Figure 5. SWV reduction traces of sensor **1**: (black line) sensor **1**; (red line) **1** with H_2PO_4^- (0.10 mmol/L); (blue line) **1** with aqueous H_2PO_4^- (25 mmol/L).

The three peaks in the SWV traces (A/B/C) were identified as follows: peak **A** corresponds to the hydrated sensor, from eq 1. This peak is almost undetectable in the SWV trace of sensor **1** alone and becomes easier to discern upon addition of hydrated anion samples.¹¹ Peak **C** appears upon addition of anion in both aqueous and nonaqueous anion samples and corresponds to the sensor–anion complex, from eq 2. The new peak, **B**, appears in the aqueous anion sample but does not appear when the anion is administered in MeCN suggesting that **B** corresponds to the hydrated sensor–anion complex, from eqs 3–5.

From the results described above and DFT calculation (B3LYP/6-31G* level),^{5b} we have inferred the qualitative insight into the binding mode and signal transduction process in sensors **1**. In the resting state, the pyrrole moieties prefer coplanar arrangement with the aromatic chromophore. The highest HOMO density is localized on the pyrroles, while

the highest LUMO density is localized at the anthraquinone. The red shift in UV–vis spectra indicates that the anion binding results in a conformational change affecting the HOMO level ($\Delta E^{\text{HOMO}} \sim 0.65$ eV) and the partial negative charge transfer¹⁵ from pyrrole to the quinoxaline-anthraquinone. This is confirmed by the electrochemical experiments, where we observe a smaller increase in LUMO energy corresponding to the cathodic-shift ($\Delta E^{\text{LUMO}} \sim 0.10$ eV) (Table 2). These observations were supported by DFT calculations for the $\mathbf{1} \cdot \text{F}^- \cdot \text{TBA}^+$ complex that show remarkable agreement with the recorded data supporting our binding model.

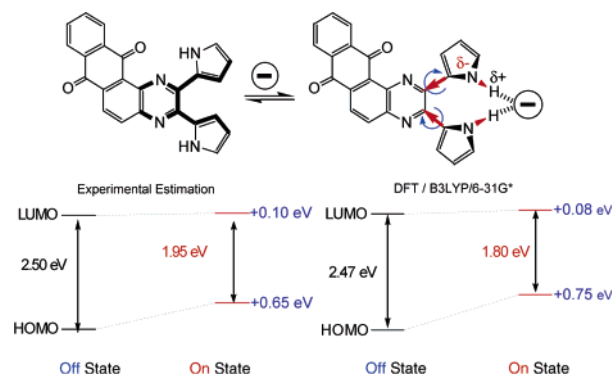


Figure 6. (Top) Signal transduction in sensor **1**: hydrogen bonding to an anion causes a conformational change and partial charge transfer to the quinone chromophore. (Bottom) Data derived from spectroelectrochemical experiments correspond to the theoretical model derived from the above binding mode.

In summary, we have demonstrated an easy-to-do approach to anion sensors that respond to the presence of anion by both change in color and redox properties. We have demonstrated that these two methods (UV–vis and SWV) may be used to cross-examine the anion sample while providing two independent output datasets to be used to distinguish between different analytes in the cases when either colorimetric or redox-based measurements may provide an ambiguous output signal. The preliminary experiments suggest that this approach may yield anion sensors potentially useful for sensing of anions in the presence of water and electrolytes. The efforts toward incorporation of these sensors into a thin-film polymer matrix and fabrication of sensing devices are under way.

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Supporting Information Available: Experimental procedures and spectroscopic data for sensors **1–3** and examples of SWV and UV–vis titration data. Details on the DFT calculations are also included. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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