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Development of Chemical Sensors Based on Redox-Dependent Receptors: *N,N'*-Dimethyldiazapyrenium-Modified Electrodes

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Electrodes modified with Nafion films containing 2,7-dimethyldiazapyrenium (DAP²⁺) were prepared and characterized with voltammetry by themselves and in the presence of organic substrates. The large, planar, electron-poor aromatic surface in DAP²⁺ facilitates π -stacking interactions with other planar aromatic molecules, particularly those that are negatively charged or electron-rich. Previous studies showed that the reduction of DAP²⁺ decreases the strength of these interactions, making the binding redox-dependent, and resulting in negative shifts in the $E_{1/2}$ of DAP^{2+/+}. This study shows that the redox-dependent binding ability of DAP²⁺ is retained in Nafion, but the selectivity is considerably different. Most significantly, the electron-rich, neutral aromatic compounds that produced small shifts in the $E_{1/2}$ of DAP^{2+/+} in solution cause much larger shifts, up to –110 mV, with the modified electrodes. With indole as a substrate, Nernstian behavior is observed (–60 mV shift per log[indole]) between 10 and 0.5 mM.

Redox-dependent receptors offer several attractive features for electrochemical sensors.¹ First, since recognition and signal transduction are combined in the same molecule, the chemical side of the sensor can be simpler than other types of electrochemical sensors where recognition and signal transduction are often divided between different chemical components. Second, like other voltammetric sensors under development,² some of the analyte limitations inherent to the common types of electrochemical sensors are removed. Unlike ion-selective electrodes, redox-dependent receptors can be directly sensitive to both neutral and ionic compounds, and unlike amperometric sensors, analytes do not need to be electroactive.

So, what is a redox-dependent receptor? In general, a receptor is a compound that selectively binds another compound (substrate) through a variety of noncovalent interactions. A *redox-dependent* receptor is one in which the binding strength to a particular substrate changes upon reduction or oxidation of the receptor. If this occurs, the redox potential of the receptor will change in the presence of the substrate. That change in redox

potential can then be used to detect and measure the concentration of substrate by electrochemical means.

The relevant equilibria for redox-dependent binding are outlined in Scheme 1. In simple terms, if a substrate S binds more strongly to the oxidized form of the receptor R ($K_{\text{ox}} > K_{\text{red}}$), then it is harder to reduce R and the redox potential of R shifts negative in the presence of S. On the other hand, if S binds more strongly to the reduced form of R ($K_{\text{red}} > K_{\text{ox}}$), it becomes easier to reduce and the redox potential shifts positive in the presence of S. Application of the Nernst equation and the equilibrium constant expressions yields eq 1. This equation predicts that the redox

$$E_{\text{obs}}^{\circ} = E_{\text{R/R}^{-}}^{\circ} + \frac{RT}{nF} \ln \left(\frac{1 + K_{\text{red}}[\text{S}]}{1 + K_{\text{ox}}[\text{S}]} \right) \quad (1)$$

potential of R will be sensitive to S over a concentration range from $\sim 1/K_{\text{red}}$ to $\sim 1/K_{\text{ox}}$. Between these extremes there will be a region where the redox potential shows the Nernstian-type response characteristic of ISEs, that is, a 60 mV/n change in potential per log[S].

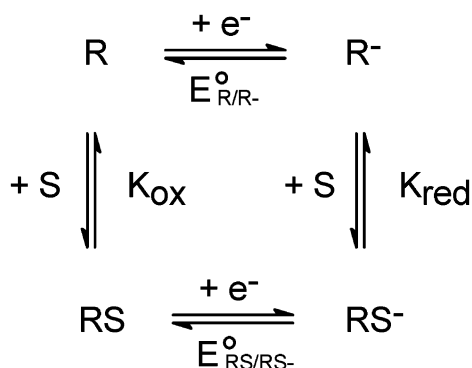
The above phenomenon is commonly observed in transition metal–ligand systems.³ In the 1980s, the concept was extended to organic hosts when a number of groups prepared redox-active crown ethers and observed large changes in redox potential in the presence of alkali metal cations.⁴ In the 1990s, further expansion to include anions⁵ and, to a lesser extent, neutral compounds⁶ occurred. The latter, which has been the focus of our work,^{1,7,8} is inherently more challenging because one cannot rely on the perturbation of strong ionic interactions to produce the redox dependence. Although there are now numerous examples of electroactive receptors for ionic compounds in which

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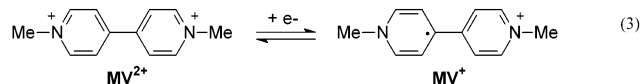
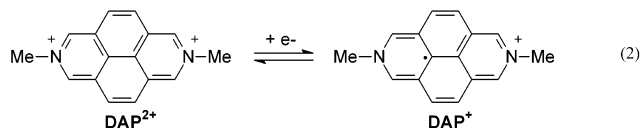
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Scheme 1



binding is strongly dependent on the redox state,^{4,5} there are still only a few examples of such receptors for neutral compounds.⁶ Part of the reason for this may be the belief that strong, selective binding by necessity requires rather elaborate molecular structure. However, this is not necessarily the case. For example, we have shown that several simple *o*-quinones can act as redox-dependent receptors toward aryl ureas in aprotic media.^{1,8}

The subject of this paper is another example of a simple molecule that can function as a redox-dependent receptor. The compound, *N,N*-dimethyl-2,7-diazapyrenium (DAP^{2+}), is an analogue of the well-known redox couple methyl viologen (MV^{2+}). Both undergo chemically reversible one-electron reductions in aqueous media to form stable radical cations, eqs 2 and 3.^{9,10}



DAP^{2+} differs from MV^{2+} in that it has a larger aromatic system and is also completely planar. This facilitates π - π -stacking interactions between DAP^{2+} and other planar aromatic systems, especially in aqueous solution where the interaction is driven by the unfavorable solvation of the large aromatic surfaces. As a result, DAP^{2+} readily intercalates between base pairs of DNA¹¹ and complexes individual nucleotides in aqueous solution.¹² In addition, Lehn and co-workers have reported very strong binding between DAP^{2+} and aromatic carboxylates in aqueous solution.¹³ This interaction should weaken upon reduction of DAP^{2+} to DAP^+ . Consistent with this prediction, previous studies by us revealed significant negative shifts in the redox potential of the $\text{DAP}^{2+}/+$

couple in the presence of planar, aromatic carboxylates in aqueous solution.¹⁰ Nonaromatic carboxylates and neutral aromatics did not produce a significant shift. This selectivity, coupled with the significant potential shift, led us to assert that DAP^{2+} is a redox-dependent receptor for aromatic carboxylates.

While our previous work focused on the behavior of DAP^{2+} in solution, any practical electrochemical sensor will require the receptor to be attached to the electrode surface. This paper begins our exploration of DAP^{2+} -modified electrodes by examining the behavior of DAP^{2+} electrostatically bound to Nafion films coated on the electrode surface.

Nafion is a polyelectrolyte that contains sulfonic acid groups dispersed on a perfluorinated carbon backbone.¹⁴ The protons on the sulfonic acid groups readily exchange with other cations in aqueous solution. In particular, the partition of large, multicharged, hydrophobic cations into Nafion is very favorable.¹⁵ These types of cations are also strongly retained, making it possible to examine the electrochemistry of redox-active organic cations in Nafion films when they are immersed in solutions that contain none of the redox-active cation. This method has been used to prepare many different types of redox-modified electrodes, including MV^{2+} ¹⁶ and other viologen-modified electrodes.¹⁷

Particularly relevant to this work is a study by Kaifer and co-workers looking at Nafion-modified electrodes containing a macrocyclic viologen.¹⁸ This molecule has been shown to act as a redox-dependent receptor to benzene and naphthalene-sized aromatics. Consistent with its behavior in acetonitrile, large negative shifts in the redox potential of the viologen in Nafion were observed in the presence of the electron-rich aromatics indole and catechol.

This study shows that DAP^{2+} also retains its ability to act as redox-dependent receptor when electrostatically bound in Nafion. However, there are some notable differences between the behavior of DAP^{2+} in solution and in Nafion. First, the sensitivity to aromatic anions that was observed in solution is lost, and second, a sensitivity to organic cations is gained. Both of these effects are a consequence of the permselectivity of Nafion. Third, and most importantly, the sensitivity of DAP^{2+} toward neutral, electron-rich aromatic compounds greatly increases. These types of compounds only cause small shifts in the redox potential of $\text{DAP}^{2+}/+$ in aqueous solution, but large shifts, up to -110 mV, are observed with some of these compounds in Nafion.

EXPERIMENTAL SECTION

Chemicals. DAP^{2+} was synthesized as the chloride salt according to the method of Hunig,¹⁹ modified as described

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previously.¹⁰ MV²⁺ was also prepared as the chloride salt as described previously.¹⁰ Nafion (1100EW form) was obtained as a 5% solution in low molecular weight alcohols from Aldrich Chemical Co.

Electrode Preparation. Glassy carbon electrodes (Bioanalytical Systems) were prepared by polishing with 0.25- μ m diamond paste, followed by an aqueous slurry of 0.05- μ m alumina. They were rinsed well with water and then allowed to air-dry.

For "solution-loaded" electrodes, the 5% Nafion solution was diluted with absolute ethanol to make a 0.1% solution. A 10- μ L aliquot of this solution was placed onto a freshly polished electrode, which was then rotated head-up at 300 rpm until the solvent evaporated. The resulting electrodes were loaded by soaking for 10–15 min in a stirred pH 7 buffer solution containing 1 mM DAP²⁺ or MV²⁺, followed by rinsing with water. The modified electrodes were soaked overnight in pH 7 buffer prior to use in electrochemical experiments.

For "preloaded" electrodes, a DAP²⁺ coating solution was prepared by dissolving 1.0 mg of [DAP]Cl₂ with 45 μ L of water, 45 μ L of ethanol, and 90 μ L of 5% Nafion. MV²⁺ coating solutions were prepared similarly using 1.7 mg of [MV]Cl₂, 90 μ L of water, 90 μ L of ethanol, and 180 μ L of 5% Nafion. Modified electrodes were made by applying a 2- μ L aliquot of the coating solution and then quickly spreading the drop across the entire end of the electrode. Immediately afterward, the electrodes were rotated head-up at 300 rpm until the solvent evaporated.

Electrochemical Experiments. All experiments were run in N₂-purged, pH 7 phosphate buffer (KH₂PO₄/K₂HPO₄, μ = 0.1). A three-electrode, single-compartment cell was used, with either a polished glassy carbon electrode or a Nafion-modified carbon electrode as the working electrode, a platinum wire counter electrode, and a SCE reference electrode. A PAR model 263 digital potentiostat with the model 270 electrochemistry software package was used for all experiments.

Concentration and D_{app} of DAP²⁺ and MV²⁺ in the Preloaded Electrodes. Electrodes used for these experiments were coated with 1.5 μ L of the preloading solutions. Using the given density of 0.874 g/cm³ for the 5% Nafion solution, a literature value of 1.58 g/cm³ for the wet density of Nafion,²⁰ and a total coating area of 0.313 cm², the wet thickness of the Nafion films was estimated to be 6.6×10^{-5} cm. Coverages for three identically prepared C/naf(DAP²⁺) and C/naf(MV²⁺) electrodes were measured by integrating cyclic voltammograms (CVs) at 2 mV/s and dividing by the active electrode area of 0.0707 cm². This gave average coverages of 3.3×10^{-8} mol/cm² for C/naf(MV²⁺) and 3.2×10^{-9} mol/cm² for C/naf(DAP²⁺). Dividing by the thickness gave average concentrations of 0.50 M for MV²⁺ and 0.048 M for DAP²⁺.

UV/visible spectroscopy was also used to calculate the concentrations of DAP²⁺ and MV²⁺. To determine the extinction coefficients, spectra for DAP²⁺ and MV²⁺ in pH 7 buffer were recorded using a Hewlett-Packard 8452 diode array spectrometer. DAP²⁺ showed a set of strong absorptions in the near-UV with λ_{max} 's at 374, 394, and 418 nm. Plots of absorption versus concentration were linear between 0.05 and 1 mM. The following extinction coefficients were determined from the slopes: 2370 (374

nm), 7380 (394 nm), and 14 000 (418 nm). MV²⁺ showed a single maximum at 256 nm. A plot of absorption versus concentration for this peak was also linear between 0.05 and 1 mM. The slope gave an extinction coefficient of 17 600.

The absorption spectra of DAP²⁺ and MV²⁺ in Nafion were recorded using preloaded films prepared on quartz slides and immersed in pH 7 buffer. The results were very similar to those observed for DAP²⁺ and MV²⁺ in solution. Concentrations were calculated using the extinction coefficients determined in solution and assuming a path length of 6.6×10^{-5} cm (the approximate wet film thickness). These calculations gave values of 0.31 M for MV²⁺ and 0.29 M for DAP²⁺.

Apparent diffusion coefficients, D_{app} , were determined from chronoamperometry experiments with the same electrodes used to measure concentrations. $D_{app}^{1/2}C$ values were calculated from the slopes of the i versus $t^{-1/2}$ plots. These calculations gave $D_{app}^{1/2}C$ values of 1.18×10^{-8} mol/(s^{1/2} cm²) for MV^{2+/+} and 1.97×10^{-9} mol/(s^{1/2} cm²) for DAP^{2+/+}. Combining these values with the UV/visible determined concentrations, gives D_{app} values of 1.4×10^{-9} cm²/s for MV^{2+/+} and 4.6×10^{-11} cm²/s for DAP^{2+/+}.

Receptor–Substrate Studies. Receptor–substrate interactions were studied by taking CVs of 1 mM DAP²⁺ solutions, C/naf-(DAP²⁺) electrodes, and C/naf(MV²⁺) electrodes in the presence of a variety of possible substrates. Solution-loaded electrodes were soaked in the solution containing substrate for 1.5 h prior to recording the CVs. Preloaded electrodes were soaked in a stirred solution containing substrate for at least 5 min prior to recording the CVs. Scans were repeated every 5 min until the peak potentials became constant. These studies indicated that equilibration with the substrate usually occurred in less than 5 min with 10 mM substrate. More time was required with lower concentrations. $\Delta E_{1/2}$ was calculated as the difference between $E_{1/2}$ in the substrate solution and that in the blank solution.

RESULTS AND DISCUSSION

Electrode Preparation. In initial experiments, the standard method, which we term "solution loading", was used to incorporate DAP²⁺ and MV²⁺ into Nafion films. In this method, the electrodes are first coated with Nafion by depositing a Nafion/alcohol solution onto the electrode. After the alcohol evaporates, the resulting Nafion films are "loaded" with electroactive cation by soaking in a solution containing the cation.

Although we were able to prepare glassy carbon electrodes modified with DAP²⁺/Nafion (C/naf(DAP²⁺)) using this procedure, the method was not entirely satisfactory. First, adhesion of the Nafion to the carbon surface was quite variable. Second, the background current changed over time, with the charging currents becoming larger and the onset of solvent reduction moving positive. Third and most problematic, $E_{1/2}$ of DAP^{2+/+} changed with time, moving to more negative potentials. Shifting was seen in the MV^{2+/+} wave as well, but the magnitude was considerably smaller, and the $E_{1/2}$ stabilized quickly.

Because of the above problems, an alternative method, which we term "preloading", was tried. In this method, a premixed solution of DAP²⁺ or MV²⁺ and Nafion is deposited on the electrode. This method was used with success in one of the early

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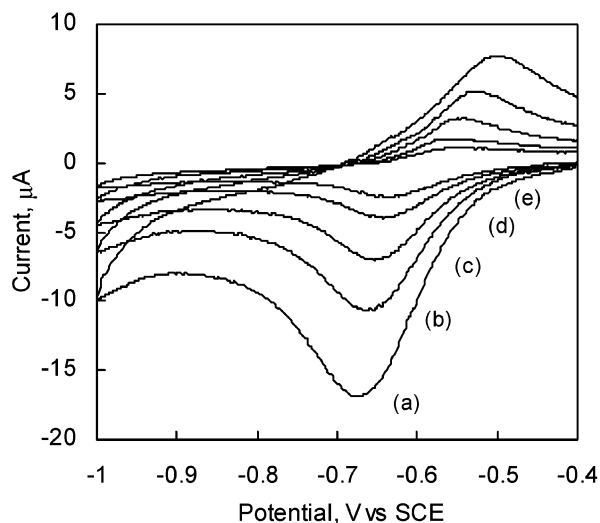


Figure 1. CVs of a preloaded C/naf(DAP²⁺) electrode in pH 7 phosphate buffer at various scan rates: (a) 200, (b) 100, (c) 50, (d) 20, and (e) 10 mV/s.

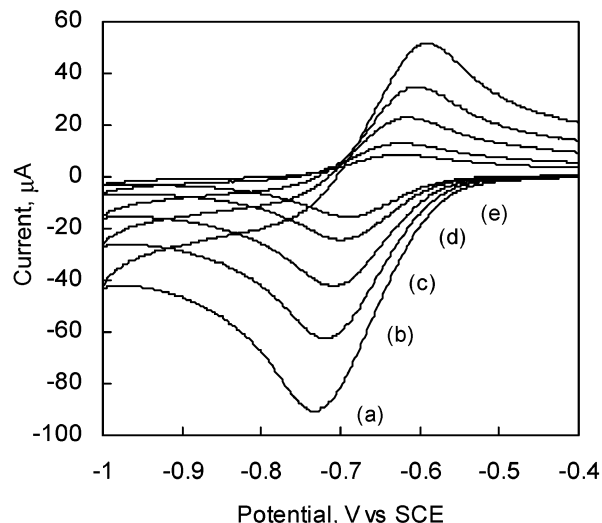


Figure 2. CVs of a preloaded C/naf(MV²⁺) electrode in pH 7 phosphate buffer at various scan rates: (a) 200, (b) 100, (c) 50, (d) 20, and (e) 10 mV/s.

studies of Nafion-modified electrodes,²¹ but it has never come into common usage. However, with DAP²⁺, it appears to be the superior method. Using the preloading method, adhesion to the electrode was not a significant problem, and the background current did not change appreciably over long periods of time. We believe this is because replacement of the protons initially in the Nafion with DAP²⁺ increases the hydrophobicity, thereby increasing adhesion to the carbon surface.

In addition, $E_{1/2}$ of DAP^{2+/+} in the preloaded films was also more stable. It is possible that the changing $E_{1/2}$ observed with the solution-loaded electrodes is due to slow redistribution of DAP²⁺ from the kinetically to thermodynamically preferred sites. The preloading method should guarantee that the DAP²⁺ is already located in the thermodynamically favorable positions so no redistribution would be needed.

Electrode Characterization. Figure 1 shows typical CVs for preloaded C/naf(DAP²⁺) electrodes in pH 7 phosphate buffer over a scan rate range of 10–200 mV/s. Figure 2 shows comparable voltammograms for preloaded C/naf(MV²⁺) electrodes. In both cases, large ΔE_p 's, which increase with scan rate, are observed, and the cathodic peak currents show a linear dependence on the square root of scan rate.

There are also some notable differences between the MV²⁺ and the DAP²⁺ electrodes. First, the overall wave shape for MV^{2+/+} is much more symmetric than that of DAP^{2+/+}. With DAP^{2+/+}, the anodic peaks are clearly smaller and broader than the cathodic peaks. This difference is inherent to the redox couples because a similar difference is seen in the solution voltammetry.¹⁰

The other very notable difference is the magnitude of the currents, which are 5 times larger for the C/naf(MV²⁺) electrode. Note that the underlying C electrode is the same in both figures and the coatings were prepared using the same number of moles of electroactive compound. Given this, possible reasons for larger current with the C/naf(MV²⁺) electrode are (i) the actual concentration of MV²⁺ is larger than the concentration of DAP²⁺

because of rapid loss of DAP²⁺ from Nafion upon immersion in electrolyte, (ii) the concentrations are the same but only a fraction of the DAP²⁺ is electroactive, or (iii) charge transport through the polymer is much more facile with MV²⁺ than DAP²⁺ so more MV²⁺ is accessible to the electrode.

The apparent amount of MV²⁺ and DAP²⁺ in the Nafion films was initially estimated from the integration of the cathodic peaks at slow scan rates as described in the Experimental Section. These calculations gave an average concentration of 0.50 M for MV²⁺, which corresponds to roughly 70% of available sites occupied, and 0.048 M for DAP²⁺, which corresponds to only 7% of the sites occupied. Since the electrodes were prepared using identical amounts of MV²⁺ and DAP²⁺, these results seemed improbable. For this reason, UV/visible spectroscopy was used as an alternative means to measure concentration. The apparent concentrations of MV²⁺ and DAP²⁺ determined in this manner were 0.31 and 0.29 M, respectively. Not only are these values very close together, they are also reasonably close to that determined for MV²⁺ using cyclic voltammetry.

The above result rules out rapid loss of DAP²⁺ from the Nafion films as an explanation for the much smaller currents. At present, we have no data that would allow us to distinguish between the other two possibilities: a large percentage of electroinactive DAP²⁺ or much slower charge transport with DAP²⁺ than MV²⁺. However, we believe the latter is the likely cause given the kinetic difficulties associated with DAP⁺ oxidation seen in the cyclic voltammetry.

The charge transport ability of redox polymer-modified electrodes is typically characterized by an apparent diffusion coefficient, D_{app} .²² Values of D_{app} for DAP²⁺ and MV²⁺ in the preloaded films were calculated from chronoamperometry data using the UV/visible determined concentrations, as described in the Experimental Section. This gives a D_{app} for MV^{2+/+} of 1.4×10^{-9} cm²/s and a D_{app} for DAP^{2+/+} of 4.6×10^{-11} cm²/s. Typical D_{app} values for redox couples in Nafion run from 10^{-7} to 10^{-12} cm²/

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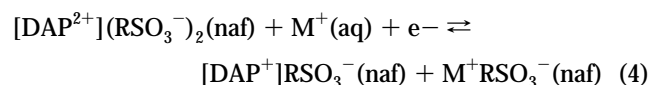
s,^{16,17,22} so the C/naf(DAP²⁺) electrodes can be characterized as having relatively slow charge transport. This would be a definite disadvantage if the intent was to use these electrodes for electrocatalysis, but it is not such a problem for making redox-dependent receptor-based sensors. In the latter case, the main requirement is that charge transport is facile enough that the voltammetric peaks can be reliably measured.

Anionic Substrates. Our previous study showed that DAP²⁺ acts as a redox-dependent receptor toward aromatic carboxylates in aqueous solution.¹⁰ The primary motivation in this study was to see if this redox dependence could be used to make a DAP²⁺-based voltammetric sensor. However, the selectivity should be quite different, since Nafion is negatively charged and is known to exclude anions. It was a surprise then to find that the solution-loaded C/naf(DAP²⁺) electrodes were sensitive to carboxylates, at least after long soaking times. For example, after soaking a solution-loaded electrode for 90 min in 10 mM 2-naphthalene carboxylate, a negative shift of -68 mV in the $E_{1/2}$ of the DAP^{2+/+} CV wave was observed, along with significant changes in wave shape.

In contrast, the preloaded electrodes behaved as expected; that is, no significant change in the voltammograms were observed after soaking the electrodes for up to 90 min in 10 mM solutions of a variety of carboxylates. This is further evidence that the preloaded films are of higher quality (fewer cracks or pinholes) than the solution-loaded ones.

Cationic Substrates. Since DAP²⁺ is a dication, strong interactions with other cations are not expected and cationic substrates would not normally be expected to produce a shift in the $E_{1/2}$ of DAP^{2+/+}. However, a cation effect can be expected with DAP²⁺ in Nafion. This is because the only additional ions that should be present in Nafion are those needed to compensate for the negative charge on the sulfonate groups. If a redox couple bound in Nafion were simply reduced with no other process occurring, the charge would no longer balance. Therefore, in order for reduction to actually occur, cations have to simultaneously migrate from solution into the film. This means that solution-phase cations are part of the overall reaction and changes in their identity and concentration will affect the observed redox potential. The quantitative rigor with which this is obeyed in Nafion was nicely demonstrated by Anson and co-workers some time ago.²³

In the case of DAP^{2+/+}, the overall redox reaction in Nafion can be summarized by eq 4. Cations that are more favorably



solvated in the more hydrophobic environment of Nafion would be expected to shift the equilibrium right, making it easier to reduce DAP²⁺ and moving the observed $E_{1/2}$ positive.

This effect is seen quite clearly in Figure 3, which shows CVs of a preloaded C/naf(DAP²⁺) electrode before and after adding 10 mM triethylamine to the pH 7 buffer. At pH 7, triethylamine is protonated so the actual species in solution is triethylammonium.

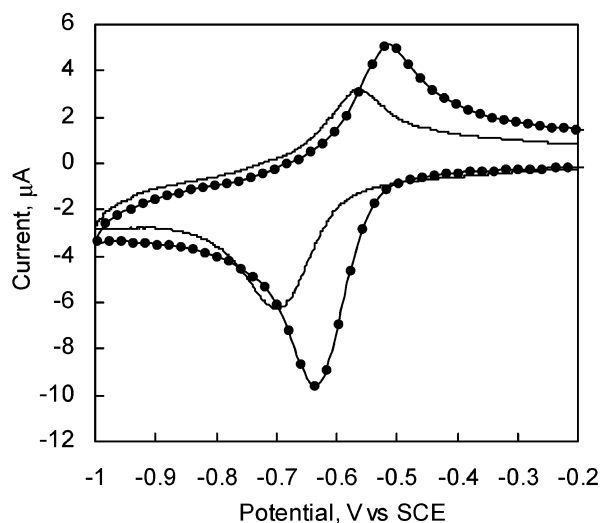


Figure 3. CVs of a preloaded C/naf(DAP²⁺) electrode in pH 7 phosphate buffer (solid line) and 10 mM triethylamine/pH 7 phosphate buffer (dotted line). Scan rate, 100 mV/s.

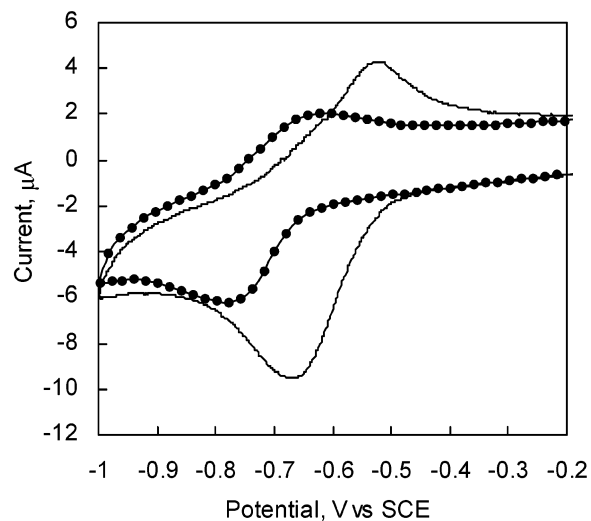


Figure 4. CVs of a preloaded C/naf(DAP²⁺) electrode in pH 7 phosphate buffer (solid line) and 1 mM 1,5-diaminonaphthalene/pH 7 phosphate buffer (dotted line). Scan rate, 100 mV/s.

This organic cation should be more favorably solvated in Nafion than the K⁺ ions present in the buffer, and indeed, a significant positive shift of +55 mV is observed.

Neutral Substrates. Although DAP²⁺ has been primarily characterized as a compound that binds organic anions in solution, there are reports of complex formation between DAP²⁺ and neutral, electron-rich organic compounds. We have also observed that some electron-rich, neutral aromatics cause small negative shifts in the $E_{1/2}$ of DAP^{2+/+} in solution. These same compounds give even larger shifts with the C/naf(DAP²⁺) electrodes. An example is 1,5-diaminonaphthalene. Addition of a 1 mM concentration of this substrate to a 1 mM DAP²⁺ solution produces a -10-mV shift in the $E_{1/2}$ of DAP^{2+/+}. The same concentration causes a -110-mV shift with the preloaded C/naf(DAP²⁺) electrodes, Figure 4. The larger shifts observed with Nafion are likely partly due to a concentration effect. Nafion provides a more favorable environment for the neutral aromatics than bulk water, so they preferentially partition in. As a result their concentration within the film is higher than their concentration in bulk solution.

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Table 1. Shifts in the Observed $E_{1/2}$ of $\text{DAP}^{2+/+}$ in the Presence of Various Neutral Substrates^a

substrates (10 mM)	$\Delta E_{1/2}$ of $\text{DAP}^{2+/+}$ (mV)		
	preloaded C/naf(DAP)	preloaded C/naf(MV)	DAP^{2+} in soln
nonaromatic			
1-butanol	-5 ± 28		
acetone	-1 ± 4		
dichloromethane	-1 ± 6		
hexane (satd)	7 ± 2		
aromatic			
benzene	0 ± 4	-3 ± 3	-1 ± 0
cyanobenzene	5 ± 8	-2 ± 1	1 ± 5
1,4-dicyanobenzene (satd)	-1 ± 3		
1,4-dihydroxybenzene	-14 ± 5	-4 ± 3	-6 ± 1
1,2-diaminobenzene	-15 ± 1	-3 ± 4	-1 ± 1
1,3-diaminobenzene	-19 ± 4	-4 ± 4	-2 ± 1
1,4-diaminobenzene	-19 ± 2	-4 ± 2	0 ± 4
indole (1 mM)	-50 ± 4		
indole	-112 ± 29	-34 ± 10	-22 ± 8
5-cyanoindole (1 mM)	-42 ± 13		
5-aminoindole (1 mM)	-66 ± 9		
naphthalene (satd)	-2 ± 3		
2,6-dihydroxynaphthalene (1 mM)	-76 ± 5		-24 ± 4
1,5-dihydroxynaphthalene (1 mM)	-87 ± 5		
1,5-diaminonaphthalene (1 mM)	-101 ± 13	-27 ± 24	-10 ± 5
quinoline	-15 ± 11	0 ± 20	-13 ± 1
8-aminoquinoline	-62 ± 3	-8 ± 6	-19 ± 9

^a $\Delta E_{1/2}$ values are the average of at least three measurements. The error values correspond to the 95% confidence limits.

Table 1 lists the average $\Delta E_{1/2}$ values observed for preloaded C/naf(DAP^{2+}) electrodes in the presence of a variety of a neutral organic compounds. For comparison, average $\Delta E_{1/2}$ values for some of the compounds with preloaded C/naf(MV^{2+}) electrodes and 1 mM DAP^{2+} solutions are also listed. As expected, the nonaromatic compounds do not have a significant effect. Benzene and the electron-poor cyanobenzenes also do not perturb the $\text{DAP}^{2+/+}$ reduction. However, modest shifts of -15 to -20 mV are observed with the electron-rich dihydroxy- and diaminobenzenes. In contrast, no significant shift is seen with these compounds with the C/naf(MV^{2+}) electrodes or with DAP^{2+} in solution.

The larger $\Delta E_{1/2}$ values, between -40 and -110 mV, are obtained with the larger electron-rich aromatic compounds, indoles, dihydroxy- and diaminonaphthalenes, and aminoquinolines. Most of these compounds appear to also give shifts with DAP^{2+} in solution, but the magnitude is much smaller. At least with indole, the C/naf(MV^{2+}) electrodes also give an experimentally significant $\Delta E_{1/2}$, but again, it is much smaller than that observed with the C/naf(DAP^{2+}) electrodes.

The trends in $\Delta E_{1/2}$ agree qualitatively with donor–acceptor considerations. DAP^{2+} is electron-poor, so electron-rich aromatics would be expected to bind more strongly to the oxidized DAP^{2+} , giving larger negative potential shifts. This is consistent with the trends observed with the indoles: amino groups are electron-donating and cyano groups are electron-withdrawing, so 5-aminoindole should interact the most strongly with DAP^{2+} , followed by indole, followed by 5-cyanoindole. The average $\Delta E_{1/2}$ follows

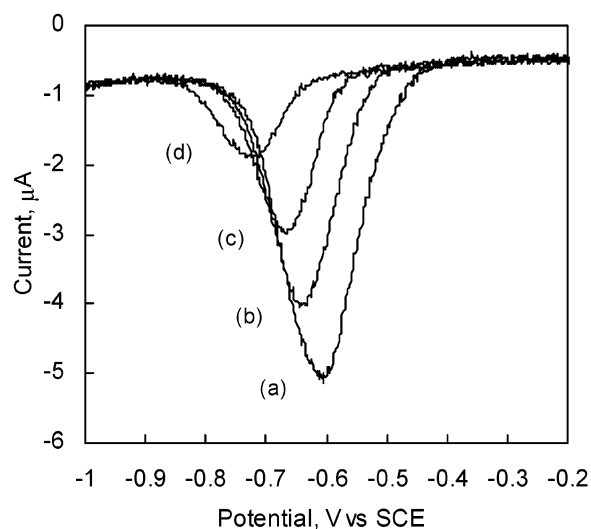


Figure 5. Differential pulse voltammograms of preloaded C/naf(DAP^{2+}) electrodes in pH 7 phosphate buffer with different concentrations of indole: (a) 0, (b) 0.2, (c) 2.0, and (d) 10 mM.

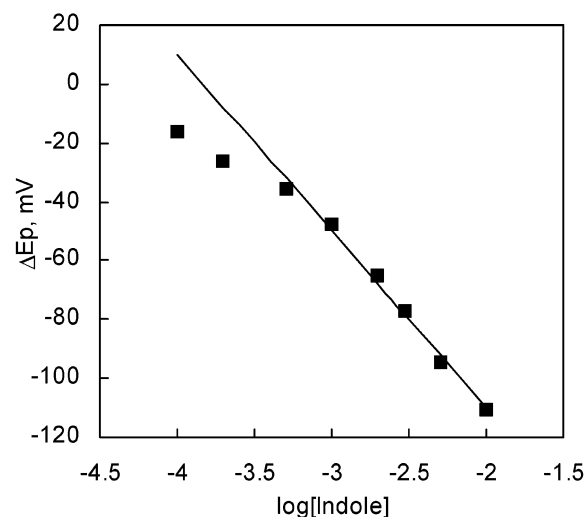


Figure 6. Average ΔE_p values from differential pulse data for preloaded C/naf(DAP^{2+}) electrodes as a function of $\log[\text{indole}]$. The line, which has a slope of -60.0 mV/ $\log[\text{indole}]$, corresponds to the best fit of the data between 0.5 and 10 mM indole

this order, although there is enough scatter in the data that the difference may not be significant. A more significant difference is observed between the two quinolines studied. Quinoline itself gives a marginal -15 ± 11 mV shift, but the more electron-rich 8-aminoquinoline gives a -62 ± 3 mV shift.

Concentration Dependence. The concentration dependence of the potential shift was evaluated using indole as a model substrate. For these experiments, differential pulse voltammetry was used. Typical results are shown in Figure 5. As expected, the peak position depends on concentration, shifting negative as the indole concentration increases. Ideally a Nernstian response is expected, that is, a -60 -mV shift per log change in indole concentration. Despite the inherent complexities of the system, this behavior is indeed observed between ~ 0.5 and 10 mM indole, Figure 6.

In addition to the change in peak potential, the current also is clearly affected by concentration, decreasing significantly as the

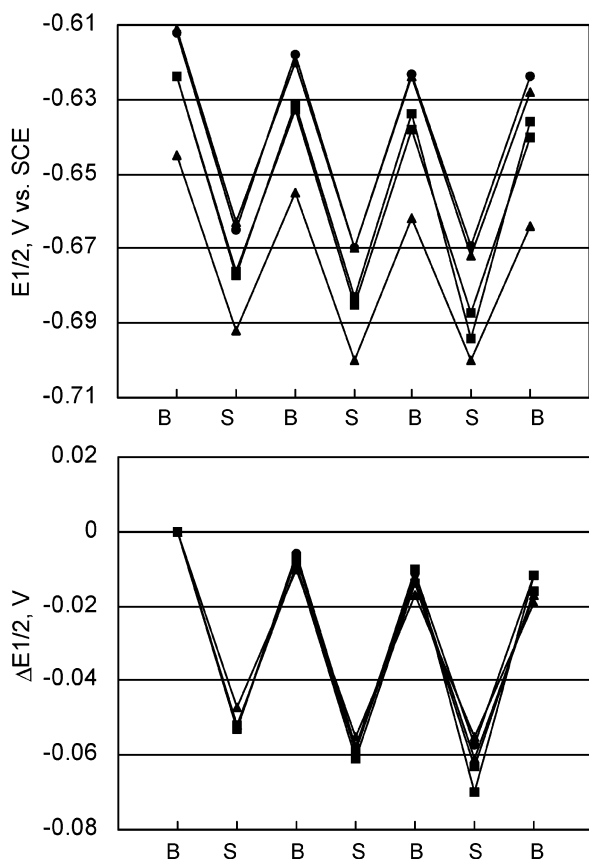


Figure 7. Top: $E_{1/2}$ values for five preloaded C/naf(DAP²⁺) electrodes moved back and forth between pH 7 phosphate buffer (B) and 1 mM indole solution (S). The markers (triangle, square, circle) represent three different underlying C electrodes. Bottom: same data as top plotted as $\Delta E_{1/2}$ values.

indole concentration increases. This behavior is always observed, although the change is not as reproducible as the potential shift. Similar behavior was observed with the macrocyclic viologen receptor studied by Kaifer and co-workers.¹⁸ They attributed the decrease in current in their system to an increase in resistance of the film as the indole concentration increased. Our data do not support this conclusion with DAP²⁺, since no significant peak broadening is observed. It simply appears that less DAP²⁺ is accessible to the electrode, perhaps because DAP²⁺ becomes less mobile due to stronger ion pairing as the organic content of the Nafion increases.

Reversibility. An important criterion for multiuse sensors is that the response to substrate be reversible. This is indeed the case with the preloaded C/naf(DAP²⁺) electrodes as shown by the data in Figure 7. The top graph gives the successive $E_{1/2}$ values for five different electrodes taken back and forth between a blank solution (B) and a 1 mM indole solution (S). These data also illustrate the large range of $E_{1/2}$ values observed for these

electrodes. The reason for this variation likely originates in inconsistencies in our coating procedure. However, it is encouraging that despite this variation in $E_{1/2}$, the $\Delta E_{1/2}$ values are remarkably similar. This is shown in the bottom graph where the same data are plotted by $\Delta E_{1/2}$. The first $\Delta E_{1/2}$ values are quite reproducible, although clearly there is increased scatter with successive cycles between blank and substrate solutions.

CONCLUSIONS

Nafion coatings provide an effective means to attach DAP²⁺ to electrode surfaces. In particular, the preloading method is a simple, convenient procedure that results in high-quality coatings in which DAP²⁺ is strongly retained. The electrochemical behavior of DAP²⁺ in these coatings appears to be very similar to that observed in solution, but the effect of substrates on the observed $E_{1/2}$ of DAP^{2+/+} is altered due to the properties of Nafion. With the preloaded electrodes, the sensitivity of DAP²⁺ to organic anions is lost and a new sensitivity to organic cations is gained. Most significantly, the response of DAP²⁺ to neutral, electron-rich aromatic compounds is enhanced over that seen in solution. Relatively small negative $\Delta E_{1/2}$'s are observed with these compounds in solution, but $\Delta E_{1/2}$'s up to -110 mV are observed with the C/naf(DAP²⁺)-modified electrodes. Furthermore, studies with indole indicate that the potential shift shows the expected Nernstian concentration dependence and is reversible.

The main significance of this work is that it demonstrates that it is possible to use a very simple redox-dependent receptor to make modified electrodes that show a reasonably selective, sensitive, and predictable response to a particular class of substrate. This is perhaps particularly noteworthy given the obviously nonideal behavior of the system studied—the DAP^{2+/+} couple shows only quasi-reversible electrochemical behavior, charge transport in the films is slow, and both the $E_{1/2}$ and CV wave shape for the DAP^{2+/+} couple vary considerably between electrodes. All these facts mean that extraction of meaningful thermodynamic information from the $\Delta E_{1/2}$ values would be very challenging. However, the requirements for sensing are not as rigorous. For sensing, what is needed is a fast, selective, reproducible, and reversible response that depends on substrate identity and concentration. We have demonstrated the latter two properties, at least in rudimentary form, with these electrodes. The response time and behavior in mixtures will be the subject of future investigations.

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