Polymeric Membranes Electrodes for Monohydrogen Phosphate and Sulfate

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A zwitterionic bis(guanidinium) ionophore bearing an anionic closo-borane cluster (1) and a dihydrochloride analogue (2) are investigated in polymeric membrane ion-selective electrodes (ISEs). Both compounds have been previously shown to complex and selectively extract oxoanions. By systematic variation of the kind and concentration of the ion-exchanger sites in the membrane, the optimal performance with the so far best sulfate selectivity is found for ISE membranes based on the dihydrochloride, whereas those with the zwitterion analogue are shown to possess a reasonably good selectivity for monohydrogen phosphate.

Although the majority of the approximately 60 ions for which ionophore-based polymeric membrane ion-selective electrodes (ISEs) have been described up to now are cations, a series of new anion-selective electrodes were introduced recently as a result of the growing interest in the host–guest chemistry of anions. It is especially challenging to achieve a useful selectivity for the strongly hydrophilic anions fluoride, phosphate, and sulfate. Various dialkyl- and diarylthiophosphate derivatives induce adequate phosphate selectivities in membranes, but their insufficient stability and short lifetime have prohibited their applicability. Good stability and excellent selectivity for HPO$_4^{2-}$ have been obtained in one case with bis(triphenyl) oxide. Another promising ionophore is a uranyl salophene that induces an excellent selectivity for H$_2$PO$_4^-$. The rather poor lower detection limit found might be due to its being used in membranes of chemically modified field effect transistors.

For sulfate, so far, the most promising ISE is based on a bis(thiourea) derivative that forms four hydrogen bonds in a 1:1 complex with SO$_4^{2-}$. Very recently, a bis(imidazoline) derivative was reported to exhibit a similar selectivity for sulfate with respect to major interferences but a strong pH dependence as well.

Guanidinium derivatives have been used as ionophores for sulfite and salicylate. Recently, the electrically neutral ditopic guanidinium compound with a covalently attached closo-borane cluster bearing two negative charges, 1, and the dihydrochloride, 2 (Figure 1), were shown to strongly bind phosphate and sulfate. A structurally similar host proved to selectively extract sulfate from an aqueous into a chloroform solution.

In this work, we show the applicability of compounds 1 and 2 as ionophores in ISEs for HPO$_4^{2-}$ and SO$_4^{2-}$, respectively.

EXPERIMENTAL SECTION

Reagents. The synthesis of the zwitterion carrier 1 has been described previously, and that of the dihydrochloride 2 will be presented elsewhere. Potassium tetrakis[3,5-bis(trifluoromethyl)phenyl]borate (K(TFPB), KBr), hexadecyltriocadecylammonium bromide (HDTODAB, RBr), 2-nitrophenyl octyl ether (ONPOE), poly(vinyl chloride) (PVC), and tetrahydrofuran (THF) were from Fluka AG (CH-8071 Buchs, Switzerland). Aqueous solutions were prepared with deionized water (specific resistivity overcompensated by selective complexation. Various dialkyl- and diarylthiophosphate derivatives induce adequate phosphate selectivities in membranes, but their insufficient stability and short lifetime have prohibited their applicability. Good stability and excellent selectivity for HPO$_4^{2-}$ have been obtained in one case with bis(triphenyl) oxide. Another promising ionophore is a uranyl salophene that induces an excellent selectivity for H$_2$PO$_4^-$. The rather poor lower detection limit found might be due to its being used in membranes of chemically modified field effect transistors.

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Influence of Ionic Sites. The response of ISE membranes containing various kinds of ionic sites can be used to distinguish whether the ionophore acts as an electrically charged or an uncharged carrier.\textsuperscript{30–32} It has been shown that ISEs with electrically neutral carriers only function if sites with a charge opposite to that of the analyte are present.\textsuperscript{30} Those with charged carriers, on the other hand, do not need the addition of sites, but in the case of 1:1 complexes of monovalent cations and negatively charged monovalent ionophores, they show improved selectivities in the presence of added sites of the same charge sign as the analyte.\textsuperscript{30–32} In this case, charged-carrier-based ISEs also respond well if the charge sign of the sites is opposite to that of the analyte; however, their selectivity is no longer influenced by the ionophore (Hofmeister selectivity sequence).\textsuperscript{20,30,33} More recent results indicate that the charge sign of the ionic sites that give the highest potentiometric selectivities depends on the charge number of the primary and interfering ions and on the stoichiometry of their complexes with the ionophore.\textsuperscript{34} The carrier mechanism of various ionophores has been evaluated on the basis of these relationships.\textsuperscript{30–32} Corresponding experiments have now been carried out with ionophores 1 and 2 (Figure 1). Thewitteron 1 with two guanidinium units has no overall net charge and, therefore, is expected to have no ion exchange properties; i.e., it should act as an electrically neutral carrier. Indeed, no anionic response is observed for ISE membranes based on 1 without added sites or with anionic sites. On the other hand, given the high basicity of guanidines, it is expected that, after conditioning, 2 in the ISE membrane remains protonated so that it acts as a charged carrier. This seems to be supported by the fact that various guanidine derivatives have been successfully used in anion-selective membranes without added ionic sites.\textsuperscript{21,22} Surprisingly, however, ISE membranes with 2 having either 50 mol % of anionic sites (relative to ionophore) or no added sites showed electrode functions with

\begin{align}
\log K_{\text{pot}}^\circ &= \frac{E^\circ_i - E^\circ}{s} 
\end{align}

(1)


\textsuperscript{29} Buck, R. P.; Lindner, E. Pure Appl. Chem. 1994, 66, 2527–2536.


a reduced slope of only ca. 45 mV/decade for monovalent anions and did not, or did not reproducibly, respond to HPO$_4^{2-}$ and SO$_4^{2-}$. According to the charged-carrier mechanism, an anionic response is expected under such conditions. Since the apparent basicity of the two guanidines is likely to be influenced by complexation, their degree of protonation depends not only on the pH of the sample solution but also on the kind of anions present in the ISE membrane. Furthermore, if a ditopic guanidinium ionophore is not fully protonated, some molecules may be doubly protonated and others not at all, depending on the complexes formed. Given the many possibilities, further mechanistic investigations will be needed to explain the above partly surprising observations.

The logarithmic selectivity coefficients, $\log K_{HPO_4}^{pot}$, obtained from the electrode responses of various ISEs based on the same ionophore but different concentrations of cationic sites (R$^+$, mol % relative to 1; Sal$^- = $ salicylate), are shown in Figures 2 and 3. In all cases, close to Nernstian slopes have been obtained with each of the anions studied so that the $K_{HPO_4}^{pot}$ values found are characteristic of the respective ISEs. The selectivity coefficients for membranes with 1 and R$^+$ concentrations of 50, 100, or 150 mol % (referred to the ionophore) differ only slightly. However, with 200 mol % of R$^+$, they tend toward those of an anion-exchanger membrane (cf. Figure 2). Interestingly, the preference for HPO$_4^{2-}$ over SO$_4^{2-}$ found for ISE membranes with 1 is reversed for those with 2. On the basis of these results and the ruggedness of the ISEs, the membrane containing ionophore 1 with 100 mol % of cationic sites has been chosen for HPO$_4^{2-}$ and that with 2 and 50 mol % of cationic sites for SO$_4^{2-}$ measurements.

**ISE for Monohydrogen Phosphate.** The various phosphate ISEs described so far in the literature respond partly to HPO$_4^{2-}$ (9,13,14,16) and partly to H$_2$PO$_4^{-}$ (15,17). Because of the possible interference by OH$^-$ and the relationship between pH and the activity of the various phosphate species, it is not always simple to decide unequivocally from the ISE response alone which anion is being sensed. Therefore, the pH of a sample with a total phosphate concentration of $5 \times 10^{-2}$ M was changed stepwise by successively adding $10^{-1}$ M NaOH and $5 \times 10^{-2}$ M NaH$_2$PO$_4$. The resulting emf responses of an ISE membrane based on 1 and of a pH glass electrode are plotted in Figure 4 as a function of pH and of the calculated HPO$_4^{2-}$ and H$_2$PO$_4^{-}$ concentrations. It is seen that the slope of the response function is near-theoretical only for HPO$_4^{2-}$ ($-32.1$ mV/decade; Figure 4, center), for OH$^-$ it is $-27.4$ mV/decade (Figure 4, left), and for H$_2$PO$_4^{-}$ as the sensed anion it would be cationic (Figure 4, right). The pH-independent response to H$_2$PO$_4^{-}$ is confirmed by another experiment (Figure 5) where the total phosphate concentration is varied at constant pH using a $10^{-2}$ M HEPES buffer (pH 7.10). Since, in this case, the lower detection limit is governed by OH$^-$ interference, the response function can be used to evaluate $K_{HPO_4,OH}^{pot}$ with the fixed-interference method (FIM; cf. Table 1). The lower detection limit for HPO$_4^{2-}$ in an unbuffered solution is $8.7 \times 10^{-8}$ M and, 

thus, is better by more than 1 order of magnitude than usually observed with polymeric ISE membranes. This improvement in the lower detection limit is probably due to the fact that, in highly diluted aqueous NaH$_2$PO$_4$ solutions, over 90% of the phosphate species is present as H$_2$PO$_4^-$ so that HPO$_4^{2-}$ is effectively buffered and the bias of the lower detection limit by phosphate species leaching from the membrane is reduced. The response of the same membrane to various anions is shown in Figure 6.

Figure 4. Potentiometric responses of an ISE membrane with 1 and 50 mol % of cationic sites (top curves) and of a pH glass electrode (bottom curves) in $5 \times 10^{-2}$ M NaH$_2$PO$_4$ at different pH values. The emf is plotted as a function of pH (log $a_{OH}$, left) as well as calculated log $a_{HPO_4^{2-}}$ (center) and log $a_{H_2PO_4^-}$ (right).

Figure 5. Potentiometric response of an ISE membrane with ionophore 1 and 100 mol % of cationic sites to HPO$_4^{2-}$ in unbuffered and HEPES-buffered (10$^{-2}$ M; pH 7.10) solutions. The change in emf upon 10-fold dilution of a 10$^{-2}$ M HEPES solution (pH 7.10) is <3 mV.

<table>
<thead>
<tr>
<th>Anion</th>
<th>$K_{pot}^{(SSM)}$ (ref 16)</th>
<th>$K_{pot}^{(SSM)}$ (ref 17)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPO$_4^{2-}$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>H$_2$PO$_4^-$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>OH$^-$</td>
<td>$-3.5$</td>
<td></td>
</tr>
<tr>
<td>OAc$^-$</td>
<td>$-1.4 \pm 0.3$</td>
<td></td>
</tr>
<tr>
<td>Cl$^-$</td>
<td>$-0.5 \pm 0.1$</td>
<td>$-3.0$</td>
</tr>
<tr>
<td>SO$_4^{2-}$</td>
<td>$-1.8 \pm 0.3$</td>
<td>$-3.2$</td>
</tr>
<tr>
<td>CO$_3^{2-}$</td>
<td>$-0.4 \pm 0.2$</td>
<td>$-3.2$</td>
</tr>
<tr>
<td>Br$^-$</td>
<td>$1.8 \pm 0.7$</td>
<td>$-2.1$</td>
</tr>
<tr>
<td>NO$_3^-$</td>
<td>$4.1 \pm 0.9$</td>
<td>$-2.4$</td>
</tr>
<tr>
<td>I$^-$</td>
<td>$8.8 \pm 1.0$</td>
<td>$0.0$</td>
</tr>
<tr>
<td>Sal$^-$</td>
<td>$8.2 \pm 0.1$</td>
<td></td>
</tr>
<tr>
<td>ClO$_4^-$</td>
<td>$9.8 \pm 0.2$</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Potentiometric Selectivity Coefficients, log $K_{pot}^{(SSM)}$ (SSM), for a HPO$_4^{2-}$ ISE with ionophore 1 and 100 mol % of HDTODAB Compared with Literature Values

- Standard deviations were obtained with three ISEs prepared from the same membrane.
- FIM.

Nernstian responses to all anions are observed except for low concentrations of CO$_3^{2-}$ and AcO$^-$. In the former case, it might be due to HCO$_3^-$ and in the latter to OH$^-$ interference. Since, at higher concentrations, the response to all anions studied is near-Nernstian, the separate solution method (SSM) can be applied to obtain unbiased $K_{pot}$ values (Table 1). For comparison, the corresponding values determined by Liu et al. and Antonisse et al. are also given. The best selectivities are found with an ISE based on bis(tribenzyltin) oxide, which, however, lacks long-term stability. In most practical applications, interference by Cl$^-$ seems to be the most important factor. From the corresponding selectivity coefficient (Table 1), it can be estimated that the lower detection limit for HPO$_4^{2-}$ in ambient water with 10$^{-3}$ M Cl$^-$ is

unbiased selectivity coefficients. These are shown in Table 2. Nernstian slopes indicate that the SSM can be used to obtain No calibration curves are available for the SO$_4^{2-}$ from the SSM or FIM. The

![Figure 7](image-url)

**Figure 7.** Potentiometric responses of an ISE membrane with ionophore 2 and 50 mol % of cationic sites to SO$_4^{2-}$ and various interfering anions (Sal$^-$ = salicylate).

about $10^{-6}$ M. Given the favorable lower detection limit of our ISE based on 1 (Figure 4), it can be further improved by diluting the samples, which in ISEs for divalent ions causes the interference from monovalent ions to be reduced. Since ISEs with the uranyl salophene ionophore respond to H$_2$PO$_4^-$ as the primary anion, they, despite the lower numerical value of log $K_{\text{pot}}^{\text{HPO}_4^-,CIV}$, suffer a stronger interference from $10^{-3}$ M Cl$^-$ and would, therefore, only be useful above ca. $10^{-3}$ M H$_2$PO$_4^-$ in ambient water, even if the current lower detection limit of ca. $10^{-3}$ M H$_2$PO$_4^-$ could be improved. Our ISE membrane based on 1 did not show significant changes (<1 mV/decade for the slopes in the linear range $10^{-2}$-$10^{-4}$ M) in its performance after storing it in the inner reference solution over 1 month. This long-term stability is an improvement with respect to the recently described HPO$_4^{2-}$ which, in turn, has a better selectivity behavior.

**ISE for Sulfate.** Except for its slight preference for SO$_4^{2-}$ over HPO$_4^{2-}$, the response to most anions observed with the ISE based on 2 is very similar to that with 1 (Figure 7). Again, the near-Nernstian slopes indicate that the SSM can be used to obtain unbiased selectivity coefficients. These are shown in Table 2 together with the literature values for the so far best SO$_4^{2-}$ ISEs. Unfortunately, selectivity factors obtained with the matched-potential method, $k_i^{\text{PM}}$, cannot be directly compared with $K_{\text{pot}}^{ij}$ from the SSM or FIM. The $K_{\text{pot}}^{ij}$ values in Table 2 (column 3) are, therefore, estimated from the calibration curves published. No calibration curves are available for the SO$_4^{2-}$ ISE based on a bis(imidazole) derivative, and unfortunately, the procedure described does not allow a reliable estimation of $K_{\text{pot}}^{SO_4^{2-}}$ values. For this ISE, therefore, upper and lower selectivity limits are given in Table 2. So far, the lowest interference from Cl$^-$ has been obtained with our ISE based on 2. The new sensor seems to be adequate for direct potentiometric monitoring of SO$_4^{2-}$ down to $10^{-6}$ M in ambient waters having $10^{-3}$ M Cl$^-$ or less. Also for this ISE, no significant change in performance has been observed after a storage period of 1 month in the inner reference solution.

**CONCLUSIONS**

The bis(guanidinium) ionophores 1 and 2, previously shown to selectively complex and extract oxoanions, are useful ionophores in ISE membranes. Compared with earlier sensors, the new ISE for HPO$_4^{2-}$ shows advantages as to stability and lower detection limit. With ionophore 2, on the other hand, the so far best ISE for SO$_4^{2-}$ has been obtained. On the basis of their selectivities, both ISEs are expected to be adequate for the environmental monitoring of ambient water, exhibiting a lower detection limit of $10^{-6}$ M HPO$_4^{2-}$ and SO$_4^{2-}$, respectively, in the presence of $10^{-3}$ M Cl$^-$. 

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(37) Selectivity factors obtained with the MPM under conditions identical to those in ref 18 are as follows (values from ref 18 in parentheses): AcO$, -1.4$ (-1.15); Cl$, -0.7$ (-0.1); HPO$_4^{2-}$, -0.2 (-1.5); Br$, -0.2$ (-1.1); NO$_3^-$, +1.5 (+1.6).