

# Chemical stability and application of a fluorophilic tetraalkylphosphonium salt in fluorous membrane anion-selective electrodes

Li D. Chen,<sup>a</sup> Debaprasad Mandal,<sup>b</sup> John A. Gladysz<sup>b</sup> and Philippe Bühlmann<sup>\*a</sup>

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The highly fluorophilic phosphonium salt  $(R_{18}(CH_2)_2)(R_{16}(CH_2)_2)_3P^+I^-$ , **1**, was used to provide cationic sites for anion-selective electrodes based on fluorous sensing membranes. The electrodes exhibited the theoretically expected “Nernstian” response slopes, and their selectivities for different anions were determined. For environmental analysis, the selective detection of perfluorooctanesulfonate and perfluorooctanoate is of particular interest. While previously reported electrodes based on a fluorophilic methyltriarylphosphonium salt suffered from  $OH^-$  interference to the extent that  $OH^-$  selectivities could not be determined, and general base catalysis caused decomposition of the phosphonium sites in the presence of weakly basic anions, electrode membranes based on **1** are much more robust. A loss of sensor response is only observed when the fluorous membranes doped with **1** are exposed to 0.1 M hydroxide solutions for 24 h. NMR and mass spectrometry show that the fluorophilic tetraalkylphosphonium cation of **1** decomposes under these extreme conditions to give two trialkylphosphine oxides and perfluoroalkylethanes. Interestingly, this decomposition is much slower than the base catalyzed exchange of the hydrogens in  $\alpha$  position to the phosphonium center, which in the presence of  $D_2O$  results in the quantitative formation of the octadeuterated tetraalkylphosphonium cation. While formation of a pentacoordinated transition state in the decomposition of **1** is likely, no pentavalent complexes of the phosphonium ion with  $OH^-$  could be observed by NMR spectroscopy.

## Introduction

Because of the extremely low polarizability of the C–F bond and the resulting weak van der Waals forces, perfluorocarbons are among the least polar and polarizable condensed phases known.<sup>1</sup> This is illustrated, for example, by the value of  $-0.41$  for perfluorooctane on the  $\pi^*$  scale of solvent polarity, where dimethyl sulfoxide and cyclohexane define 1 and 0, respectively.<sup>2</sup> Perfluorinated amines and perfluoroethers exhibit an equally low polarity since their numerous strongly electron-withdrawing fluorines efficiently decrease the electron density at their nitrogen and oxygen atoms, nearly eliminating any complexing capabilities.<sup>3–6</sup> To emphasize their unique properties, perfluorinated organic compounds that are not freely miscible with hydrocarbons have been referred to as being fluorous.<sup>7</sup> A variety of such compounds have been developed and are used in many application fields, such as the electronics industry, aerospace engineering, medical sciences, the cosmetic industry and phase transfer catalysis.<sup>1,8–12</sup> Besides their immiscibility with typical common oils, fluorous compounds benefit from a very high chemical inertness. These properties are also crucial for ion-selective electrodes (ISEs)<sup>13–16</sup> with fluorous sensing membranes, which have been

developed recently. The extraction of lipids and hydrophobic proteins into the hydrophobic membranes of conventional ISEs causes signal drifts and selectivity losses.<sup>17,18</sup> Therefore, the poor solubility of these lipophilic compounds in fluorous sensing membranes is of considerable interest for measurements in real-life samples such as blood or urine. Moreover, due to the extremely poor solvation of interfering ions, fluorous membrane ISEs have been found to exhibit greater selectivity.<sup>3,4,19</sup>

The selectivity of these ISE membranes arises from similar equilibria between two mutually immiscible phases as they are also observed in solvent extraction, chromatography, and biphasic catalysis. To achieve selective response to either cations or anions, ISE membranes contain ionic functional groups (so-called ionic sites) that are either covalently attached to a polymer backbone or are part of a very hydrophobic salt that readily dissolves in the hydrophobic sensing membrane.<sup>15</sup> When a hydrophobic ISE membrane is put into contact with an aqueous sample containing ions with a charge sign opposite to that of the ionic sites, those sample ions can enter the ISE membrane and create an electrical potential difference across the sample/membrane interface. The measured potential increases with the logarithm of the ion activity in the sample. The selectivity of the ISE membrane for different ions of the same charge sign is determined by the free energy of transfer from the aqueous sample into the sensing membrane. Therefore, ion-selective electrodes typically respond much more strongly to weakly hydrated ions than to very hydrophilic ions.

<sup>a</sup> University of Minnesota, Department of Chemistry, 207 Pleasant St. SE, Minneapolis, Minnesota 55455, USA. E-mail: buhlmann@umn.edu

<sup>b</sup> Texas A&M University, Department of Chemistry, PO Box 30012, College Station, Texas 77842, USA

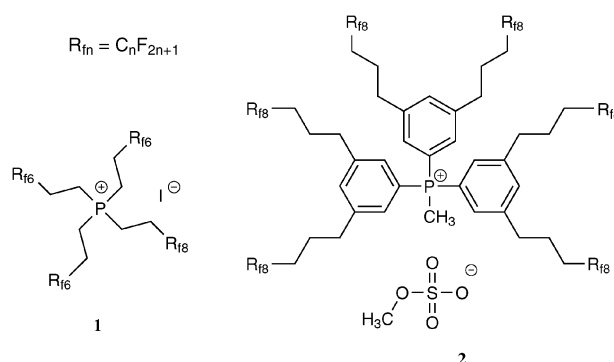
The first reported ISEs with fluorous membranes incorporated the fluorophilic tetrakis[3,5-bis(perfluorohexyl)phenyl]borate as anionic site, providing for cation selectivity.<sup>3,4</sup> More recently, the selectivity of such cation-exchanger ISEs has been modified by adding into the sensing membranes not only ionic sites but also a fluorophilic ionophore that selectively forms a complex with the target cation. This permitted the fabrication of highly selective pH electrodes.<sup>19</sup>

To extend the fluoruous sensor system to anion sensing, a fluorophilic cationic site was needed. However, since fluoruous phases have such an extremely low polarity and polarizability, they are inherently poor solvents for ionic compounds. Therefore, it is not surprising that only very few such compounds have been described in the literature.<sup>8</sup> Importantly, no suitable ammonium salt is currently available for applications in ISEs. Several fluorophilic primary and secondary ammonium salts have been reported,<sup>8,20</sup> but the possibility of deprotonation of their  $\text{NH}_3^+$  and  $\text{NH}_2^+$  groups renders them inept as cationic sites. A remarkable bicyclic compound with a quaternary ammonium group at the spiro bridgehead proved to be very effective as phase transfer catalyst and would be very promising for sensing applications if its synthesis were not based on 11 steps, limiting its availability.<sup>21</sup> Finally, while the tris(perfluorooctyl)propyl)methylammonium cation has been shown to solubilize polyoxymetalates very efficiently in perfluorohydrocarbons,<sup>22</sup> the salts of this cation with small singly charged anions such as chloride were found to be poorly soluble in perfluorocarbons such as perfluoroperhydrophenanthrene.<sup>23</sup>

An interesting alternative to fluorophilic ammonium ions are fluorophilic phosphonium cations. Fluorophilic tetraalkylphosphonium and trialkylphenylphosphonium salts as well as their application in phase transfer catalysis have been reported.<sup>8,9,24–27</sup> The first fluorophilic phosphonium salt used to prepare fluorous sensing membranes for a potentiometric anion sensor was tris{3,5-bis[(perfluorooctyl)-propyl]phenyl}-methylphosphonium methyl sulfate, **2**. The sensor membranes based on this methyltriarylphosphonium salt exhibited the theoretically expected (Nernstian) response to several anions such as  $\text{NO}_3^-$ ,  $\text{I}^-$ , and  $\text{Br}^-$ , and an excellent selectivity for perfluoroalkyl-carboxylates and -sulfonates. However, notable exceptions were observed for the basic anions  $\text{F}^-$ ,  $\text{OAc}^-$ ,  $\text{NO}_2^-$ , and  $\text{HCO}_3^-$ , for which much slower responses and long-term drifts occurred. This could be explained by the decomposition of the phosphonium salt in the presence of water according to a general base mechanism, resulting in the elimination of one aryl group and formation of phosphine oxide.<sup>23</sup> For measurements in alkaline media and for the determination of basic anions, alternative fluorophilic sites were needed.

In the work reported here, we used the fluorophilic tetra-alkylphosphonium salt  $(R_{f8}(CH_2)_2)(R_{f6}(CH_2)_2)_3P^+I^-$ , **1**, to provide cationic sites for ionophore-free anion-selective electrodes. The response and selectivity of the resulting sensors was determined in potentiometric experiments. While the resulting sensor membranes were chemically much more robust than the earlier reported ones based on the methyl-triarylphosphonium derivative **2**, a loss of response was observed upon exposure to very alkaline solutions. Mass

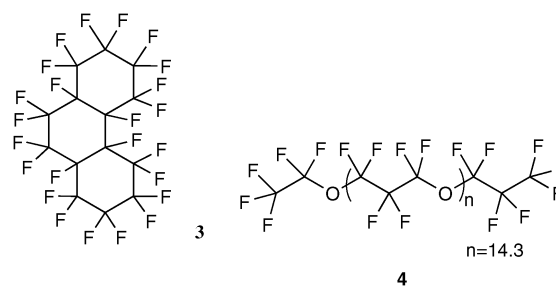
spectrometry and  $^{31}\text{P}$  and  $^1\text{H}$  NMR spectroscopy were used to elucidate the mechanism of the decomposition of **1** when exposed to aqueous solutions of high pH.



## Experimental

## Reagents and materials

(R<sub>f8</sub>(CH<sub>2</sub>)<sub>2</sub>)(R<sub>f6</sub>(CH<sub>2</sub>)<sub>2</sub>)<sub>3</sub>P<sup>+</sup>I<sup>−</sup>, **1**, was synthesized by reaction of a fluororous tertiary phosphine, (R<sub>f6</sub>(CH<sub>2</sub>)<sub>2</sub>)<sub>3</sub>P, with R<sub>f8</sub>(CH<sub>2</sub>)<sub>2</sub>I in DMF at 120 °C in a N<sub>2</sub> atmosphere, as reported previously.<sup>9</sup> Perfluoroperhydrophenanthrene, **3**, and the linear perfluoropolyether α-(heptafluoropropyl)-ω-(pentafluoroethoxy)-poly[oxy(1,1,2,2,3,3-hexafluoro-1,3-propanediyl)], **4**, were obtained from Alfa Aesar (Ward Hill, MA, USA). Fluoropore membrane filters (pure polytetrafluoroethylene (PTFE), 47 mm diameter, 0.45 μm pore size, 50 μm thick, 85% porosity) were purchased from Millipore (Bedford, MA, USA). The potassium and sodium salts were obtained from Mallinckrodt Baker (Paris, KY, USA). All sample solutions were prepared using deionized and charcoal-treated water (0.182 MΩ cm resistance) purified in a Milli-Q PLUS reagent-grade water system (Millipore). Perfluorohexanes (FC-72) was purchased from 3M (St. Paul, MN, USA) and α,α,α-trifluorotoluene from Oakwood products (West Columbia, SC, USA).



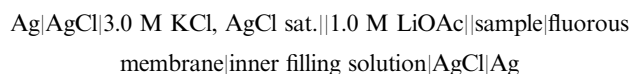
## Electrodes

Membrane supports were prepared from Fluoropore filters sandwiched between two note cards and cut to a 13 mm diameter with a hole punch. Supported liquid membranes were obtained by addition of approximately 50  $\mu\text{L}$  of  $(\text{R}_{18}(\text{CH}_2)_2)(\text{R}_{16}(\text{CH}_2)_2)_3\text{P}^+\text{I}^-$ , **1** (2 mM), in perfluoroperhydropheanthrene, **3**, onto a stack of two porous filter supports until the supports changed from opaque white to translucent with a glossy surface. These supported liquid membranes were then mounted into custom-machined poly(chlorotrifluoroethylene) electrode bodies and sealed with screw caps with a 8.3 mm diameter hole exposing the

membranes to the sample solutions.<sup>4</sup> The solution inside each electrode was typically 1 mM KCl in contact with a AgCl-coated Ag wire. However, for the measurements of the selectivities of the perfluorinated organic anions, 0.1 mM solutions of sodium perfluorooctanoate were used as inner filling solutions. The electrodes were conditioned in solutions of the target ion (primary ion) for 2–3 h prior to measurements.

### Potentiometric measurements

The electrodes made in the way described above were used in combination with a double-junction type external reference electrode (DX200, Mettler Toledo, Switzerland; 3.0 M KCl saturated with AgCl as inner-filling solution and 1.0 M LiOAc as bridge electrolyte):



Potentials were monitored with an EMF 16 potentiometer (input impedance 10 T $\Omega$ ) controlled with EMF Suite 1.03 software (Lawson Labs, Malvern, PA, USA). DC resistances of the fabricated electrodes were measured by comparing measured potentials with and without a known shunt.<sup>28,29</sup> Calibration curves were obtained by measuring the EMF while successively diluting a concentrated solution. Nernstian responses were confirmed for all anions of interest in the concentration range where selectivities were measured. Selectivity coefficients were determined with the separate solution and fixed interference methods<sup>30,31</sup> and averaged for three electrodes, giving typical deviations of  $\pm 0.3$ . All EMF values were corrected with the Henderson equation for liquid-junction potentials.<sup>32</sup> Activity coefficients were calculated according to a two-parameter Debye–Hückel approximation.<sup>33</sup>

### Spectroscopy experiments

<sup>1</sup>H NMR spectra were recorded on a Varian Inova 500 spectrometer (Varian, Palo Alto, CA, USA) with D<sub>2</sub>O in a capillary for locking and referencing purposes. <sup>31</sup>P NMR spectra were recorded on a Varian Inova 300 spectrometer with 5% H<sub>3</sub>PO<sub>4</sub>/95% D<sub>2</sub>O (wt/wt) in a capillary for locking and referencing. All spectra were recorded with a solvent mixture of perfluoroperhydrophenanthrene and perfluorohexanes in a volume ratio of 1 : 4.

Mass spectra were recorded on a reflectron ESI-TOF spectrometer (BioTOF II, Bruker Daltonics, Billerica, MA, USA). For good sample solubility and ionization, a mixture of methanol and  $\alpha,\alpha,\alpha$ -trifluorotoluene with a volume ratio of 1 : 1 was used as the solvent.

## Results and discussion

### Response and selectivity of fluorous membrane ISE membranes

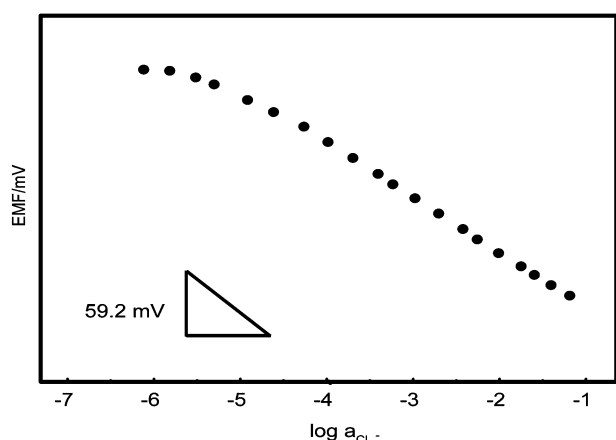
To prepare an ISE membrane, the salt providing the ionic sites is dissolved in a hydrophobic inert matrix. The latter may be a liquid supported by a highly porous inert structure or a polymer that is typically blended with a plasticizer to increase ion mobilities and thereby lower the electrical resistance. As previously reported, the use of the linear

perfluoropolyether, **4**, for the plasticization of the perfluoropolymer Teflon AF2400<sup>34</sup> and its use in cation-selective electrodes is very successful and permitted long-term stabilities of at least one month.<sup>5</sup> Therefore, we first investigated the possibility of preparing fluorous anion-selective membranes by imbibing a porous inert Teflon filter with solutions of the fluorophilic phosphonium salt, **1**, in the linear perfluoropolyether. Unfortunately, it was found that **1** is sparingly soluble in the linear perfluoropolyether. The solubility was lower than 0.25 mM. Moreover, the electrical resistance of the approximately 50  $\mu\text{m}$  thick membranes (diameter  $\approx$  8.3 mm) was 400 G $\Omega$ . This extremely high value results not only from the low solubility but also from a high level of ion pairing, which is typical for fluorous solvents.<sup>4,35</sup> Since this high resistance made potentiometric measurements difficult, all subsequent experiments were performed with solutions of the fluorophilic salt, **1**, in perfluoroperhydrophenanthrene, **3**, as the fluorous sensing phase, supported again by an inert porous Teflon filter.

The solubility of **1** in perfluoroperhydrophenanthrene, **3**, was significantly higher than in the linear perfluoropolyether **4**, so that 2.0 mM solutions could be prepared without difficulties. The resistance of the thus prepared fluorous anion-exchanger membranes were measured to be  $5.6 \pm 0.3$  G $\Omega$ , which is sufficiently low to permit potentiometric measurements without complications. Interestingly, this resistance was much lower than that of the fluorous anion selective membranes with the same concentration of the methyltriarylphosphonium salt **2** (2 mM) in the same fluorous solvent. Indeed, sensing membranes containing the latter could only be used when a fluorophilic electrolyte salt was added to lower the electrical resistance.<sup>23</sup> Without a more thorough study of ion pair formation in fluorous solutions of **1** and **2**, the reasons for this big difference cannot be identified with certainty. However, charge delocalization in the methyltriarylphosphonium unit would be expected to disfavor ion pair formation, which is just the opposite of the observed trend. Therefore, it appears likely that steric effects dominate, favoring ion pairs of the sterically only poorly shielded methyltriarylphosphonium ion **2**. Evidently, the tendency to form electrically neutral ion aggregates can limit the usefulness of a fluorophilic salt just as much as a limited solubility.

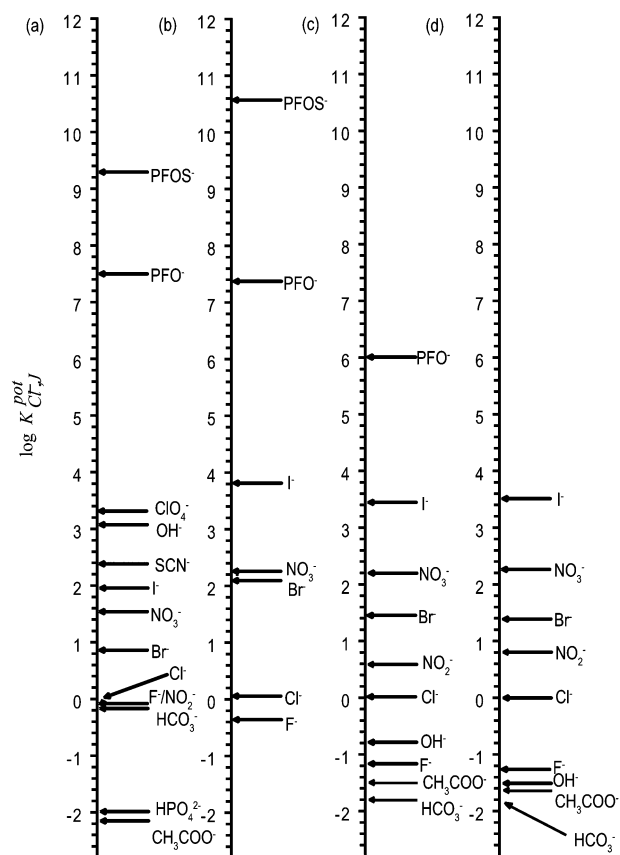
For potentiometric measurements of chloride, electrodes with fluorous sensing membrane containing **1** (2 mM) in perfluoroperhydrophenanthrene, **3**, were equilibrated prior to their first use with an aqueous 0.1 M KCl solution for 2 h. This so-called conditioning removes the iodide originally introduced into the membranes with **1** by exchange with the chloride from the aqueous solution. Once conditioned, the electrodes respond within seconds to different concentrations of chloride. Calibration curves (Fig. 1) show that the electrodes exhibited the expected theoretical (“Nernstian”) response with a slope of  $-59.2$  mV per ten-fold increase in the activity of Cl<sup>−</sup>. The detection limit was reached at  $10^{-5.6}$  M, where the potential remains unchanged upon further decreasing the Cl<sup>−</sup> activity.

The selectivity is undoubtedly the most important property of an ISE since it determines the reliability of the measurement of the target ion I in the presence of interfering ions, J. It is



**Fig. 1** Potentiometric  $\text{Cl}^-$  response of an ISE based on a liquid membrane containing **1** (2 mM) in perfluoroperhydrophenanthrene, **3**.

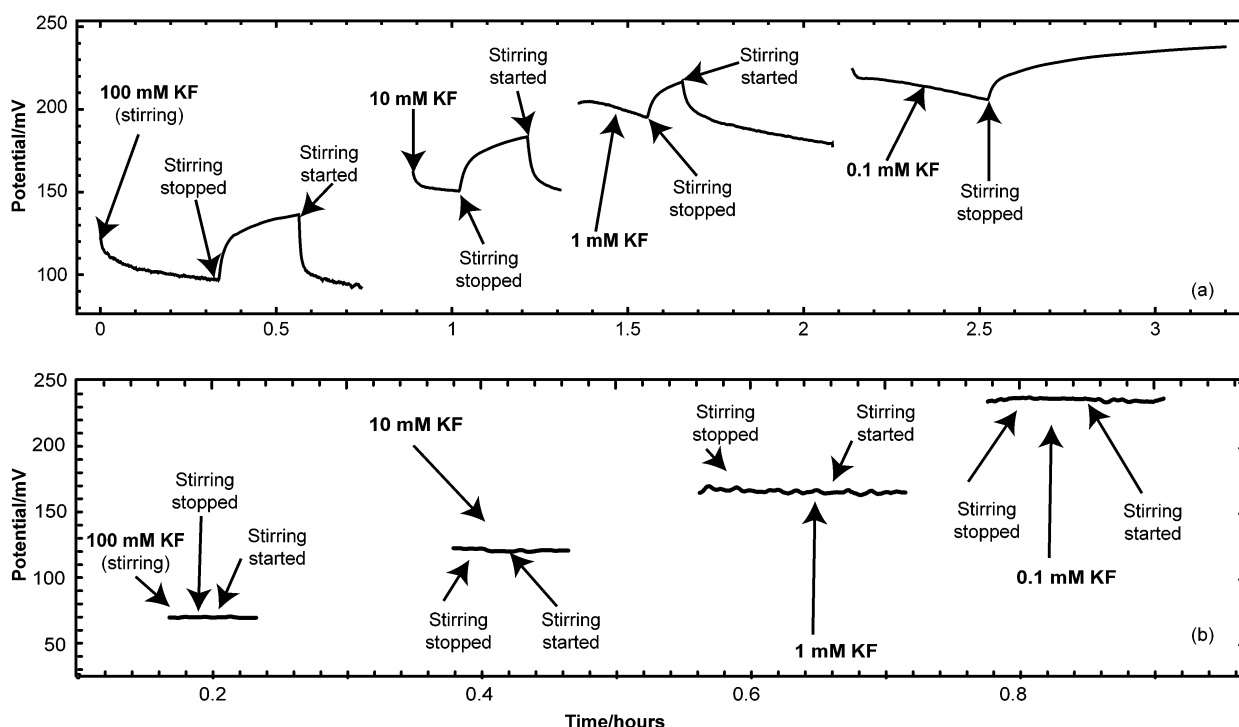
commonly quantified by the selectivity coefficient,  $K_{IJ}^{\text{pot}}$ , which for ions of the same charge equals the ratio of the activities of ion I and ion J that produce the same potential in separate measurements.<sup>30,31</sup> Fig. 2 shows the selectivity coefficients for the fluorous ISE membranes containing cationic site **1** or **2** along with corresponding values for conventional poly(vinyl



**Fig. 2** Logarithmic representation of the selectivities of two fluorous anion-exchanger membranes (a: 2 mM **1** in **3**; b: 2 mM **2** in **3**) and two PVC-based anion-exchanger membranes (c: PVC/chloroparaffin membrane containing 5% wt tridodecylmethylammonium chloride; d: PVC/*o*-NPOE membrane containing 5% wt tridodecylmethylammonium chloride). Selectivities for (b) from ref. 23.

chloride) (PVC) membranes plasticized by 2-nitrophenyl octyl ether (*o*-NPOE) or chloroparaffin. Since both **1** and **2** are poorly soluble in *o*-NPOE or chloroparaffin, tridodecylmethylammonium chloride was used in the PVC-based membranes as the anion exchanger site instead of **1** or **2**. For most ions, the selectivities of the new fluorous membranes based on cationic site **1** are similar to those of non-fluorous membranes. As expected for ion-exchanger membranes without added ionophore, the selectivities follow for most investigated ions the so-called Hofmeister series, *i.e.*,  $\text{I}^- > \text{NO}_3^- > \text{Br}^- > \text{Cl}^- > \text{F}^- > \text{CH}_3\text{COO}^-$ , a sequence that is dominated by the hydration energies of these ions in the aqueous phase. Unlike in the case of cation-selective electrodes,<sup>3</sup> the range of selectivities for these common ions was not much wider for the fluorous than for the non-fluorous membranes. However, as similarly found for membranes based on the less stable cationic site **2**, the membranes with **1** exhibited very high selectivities for the perfluorinated anions perfluorooctanoate ( $\text{PFO}^-$ ) and perfluorooctanesulfonate ( $\text{PFOS}^-$ ). While the  $\text{PFOS}^-$  selectivities of the PVC membranes could not be determined because of the limited solubility of  $\text{PFOS}^-$  in water and the high detection limit of the PVC membranes, the  $\text{PFO}^-$  selectivities of the two fluorous types of membranes were found to exceed those of the PVC/chloroparaffin membranes by approximately 1.5 orders of magnitude. Among all the investigated ions, only hydroxide exhibited a selectivity very different from what is expected based on the Hofmeister series. In comparison to the PVC-based ISEs, the fluorous membrane ISE based on cationic site **1** showed an increase in hydroxide response by approximately four orders of magnitude. The selectivities for the other anions did not differ much from those of the PVC-based ISEs, but a somewhat increased response to the weakly basic anions  $\text{F}^-$  and  $\text{HCO}_3^-$  and a slightly higher discrimination of  $\text{I}^-$ ,  $\text{Br}^-$ , and  $\text{NO}_3^-$  were observed. Detection limits for different anions of the membranes with site **1** fell in the range of  $10^{-4}$  to  $10^{-8}$  M and followed the same pattern as its selectivities. For example, in the course of the determination of selectivity coefficients with the separate solution method, detection limits of  $10^{-3}$ ,  $10^{-5}$ , and  $10^{-5}$  M were observed for the highly discriminated ions  $\text{OAc}^-$ ,  $\text{F}^-$ , and  $\text{NO}_2^-$ , respectively. On the other hand, preliminary experiments with these perfluoroperhydrophenanthrene-based membranes showed detection limits lower than  $10^{-7}$  M and  $10^{-8}$  M for  $\text{PFO}^-$  and  $\text{PFOS}^-$ , respectively. Experiments to exploit the high selectivity for perfluoroalkyl anions in mechanically more robust perfluoropolymer membranes with 3-dimensionally ordered nanoporous carbon (3DOM C)<sup>36,37</sup> as solid contacts are in progress in our laboratories. The sensitivities for all these ions lie in the range of  $-58 \pm 2$  mV per tenfold increase in anion activity, and the response times of these electrodes are less than 10 s.

Unlike in the case of the fluorophilic methyltriarylphosphonium cation **2**, ISE membranes based on the cationic site **1** did not exhibit short-term drifts in the responses to hydroxide and basic anions. As reported previously, exposure of fluorous solutions of the methyltriarylphosphonium salt **2** to  $\text{OH}^-$ ,  $\text{F}^-$ ,  $\text{OAc}^-$ ,  $\text{NO}_2^-$ , and  $\text{HCO}_3^-$  in the presence of traces of water resulted in noisy responses and long response times due to dearylation and the formation of a diphenylmethylphosphine oxide.<sup>23</sup> In the case of  $\text{F}^-$ ,  $\text{OAc}^-$ ,  $\text{NO}_2^-$ , and  $\text{HCO}_3^-$ , the



**Fig. 3** Fluoride response of fluorophilic anion exchanger (panel a: cationic site **2**; panel b: cationic site **1**) electrodes to KF solutions of different concentrations. Inner filling solution of ISEs: 1 mM KF. Panel (a) adapted from ref. 23.

decomposition of **2** involved general base catalysis, resulting in the formation of  $\text{OH}^-$  by proton transfer from water to these weak bases. Short term drifts in the potentiometric responses caused by this decomposition are illustrated in Fig. 3a for the  $\text{F}^-$  response of an electrode based on **2**. As Fig. 3a shows, the measured potentials consistently dropped when stirring was started, and increased when stirring was stopped. Sudden changes in the potentiometric response due to stirring were caused by local changes in analyte activities at the sample/membrane phase boundary, caused by the ongoing decomposition of **2**.<sup>†</sup> This was further confirmed by observation of the phosphine oxide formation by mass spectrometry.<sup>23</sup>

The same type of stirring experiment in  $\text{F}^-$  solutions was also performed for ISE membranes doped with the cationic site **1**. As Fig. 3b shows, unlike the membranes doped with **2**, the membranes containing cationic site **1** did not exhibit a stir rate dependence of the  $\text{F}^-$  response. This shows that **1** is much more resistant to decomposition by general base catalysis than **2**. Indeed, the above described measurements of the selectivities of ISE membranes based on **1** for  $\text{Cl}^-$  over  $\text{OH}^-$  were only possible because, unlike for membranes doped with **2**, the short-term stability of the  $\text{OH}^-$  response of these membranes was much higher. Only when membranes doped with **1** were stored for 24 h in 0.1 M NaOH, were potentiometric responses to  $\text{Cl}^-$  no longer observed. Decomposition of the phosphonium compound **2** was not observed when it was incorporated into ISE membranes and exposed to other anions, such as  $\text{I}^-$ ,  $\text{Br}^-$ ,

and  $\text{NO}_3^-$ , and even the weakly basic anions  $\text{F}^-$ ,  $\text{OAc}^-$ ,  $\text{NO}_2^-$ , and  $\text{HCO}_3^-$ , as evidenced by the continued flawless responses for well over 24 h.

#### Spectroscopic confirmation of the decomposition of $(\text{R}_{18}(\text{CH}_2)_2)(\text{R}_{16}(\text{CH}_2)_2)_3\text{P}^+\text{I}^-$

The unexpectedly strong  $\text{OH}^-$  interference of the ISE membranes based on the cationic salt **1**, the eventual loss of anion response upon prolonged  $\text{OH}^-$  exposure, and also the somewhat larger than expected selectivities for the weakly basic anions  $\text{F}^-$  and  $\text{HCO}_3^-$  warranted further study. While only few reports of the coordinative binding of inorganic anions to tetraalkylphosphonium ions are known, both pentavalent  $\text{NO}_2^-$  and  $\text{F}^-$  adducts have been described.<sup>38–40</sup> Therefore, it seemed possible that a pentacoordinated  $(\text{R}_{18}(\text{CH}_2)_2)(\text{R}_{16}(\text{CH}_2)_2)_3\text{POH}$  species might form due to the extremely low polarity of fluorous solvents—unfavorable to any ionic species—and enhanced Lewis acidity due to the strongly electron-withdrawing properties of the four perfluoroalkylethyl groups. Because of the oxophilicity of phosphorus,  $\text{OH}^-$  binding to phosphonium cation would be expected to be stronger than coordination of other anions, offering a plausible explanation for the larger than expected  $\text{OH}^-$  interference observed for ISE membranes based on the fluorophilic phosphonium cation **1**. This hypothesis was tested by  $^{31}\text{P}$  NMR spectroscopy. The  $^{31}\text{P}$  chemical shifts of symmetrically substituted phosphonium compounds,  $\text{PR}_4^+$ , can be found in the range of approximately +20 to +45 ppm, while  $^{31}\text{P}$  chemical shifts of pentacoordinated phosphorus compounds are in the range of –90 to –60 ppm.<sup>41</sup> As expected,  $^{31}\text{P}$  NMR spectroscopy showed a singlet with the

<sup>†</sup> Note that transmembrane ion fluxes between the inner filling solution of the ISE and the sample can also cause similar stirring dependencies of the potentiometric signal, but that the potential change would be in opposite direction when the inner filling solution has a higher or lower concentration than the sample.

chemical shift of  $\delta_P + 39.79$  for solutions of the iodide salt **1** in perfluoroperhydrophenanthrene/perfluorohexane (1 : 4 v/v). When a perfluoroperhydrophenanthrene solution of **1** (2 mM) was stirred at room temperature for 24 h in contact with an aqueous 0.1 M KOH solution and then diluted with perfluorohexane for a  $^{31}\text{P}$  NMR measurement, the signal at +39.79 ppm disappeared, and a new singlet at +36.58 ppm was observed. This is consistent with the formation of a trialkylphosphine oxide since the  $^{31}\text{P}$  chemical shifts of  $\text{R}_3\text{P}(\text{=O})$  and the corresponding tetraalkylphosphonium species are quite similar.<sup>41</sup> No signal that could be attributed to a pentacoordinated phosphorus species was observed. The  $^{31}\text{P}$  NMR data, along with the fact that the electrodes with the perfluoroperhydrophenanthrene solution of **1** lost response to  $\text{Cl}^-$  after  $\text{KOH}/\text{H}_2\text{O}$  exposure, lead to the conclusion that in extremely alkaline conditions such as  $\text{pH} = 13$ , the phosphonium cation  $(\text{R}_{18}(\text{CH}_2)_2)(\text{R}_{16}(\text{CH}_2)_2)_3\text{P}^+$  slowly decomposes to form two phosphine oxides, *i.e.*,  $(\text{R}_{18}(\text{CH}_2)_2)(\text{R}_{16}(\text{CH}_2)_2)_2\text{P}=\text{O}$  and  $(\text{R}_{16}(\text{CH}_2)_2)_3\text{P}=\text{O}$  (see Fig. 4). This interpretation was further substantiated by high resolution mass spectrometry.

Electrospray ionization mass spectra of the tetraalkylphosphonium salt **1** show the tetraalkylphosphonium ion at  $m/z$  1519 as the only positively charged ion with an appreciably intense signal. However, after a solution of **1** in perfluoro(perhydrophenanthrene), **3**, was equilibrated with an 0.1 M KOH aqueous solution for 24 hours, the signal at  $m/z$  1519 was much less intense. The two signals at 1226.9571 and 1126.9635 that were observed instead agree within error with the  $\text{K}^+$  adducts of the two trialkylphosphine oxides shown in Fig. 4 (theoretical: A, 1226.9576; B, 1126.9640). Using  $\text{NaOH}/\text{D}_2\text{O}$  instead of  $\text{KOH}/\text{H}_2\text{O}$  shifted the two most intense peaks by 10 u, which cannot be explained by the mass difference of  $\text{K}^+$  and  $\text{Na}^+$  alone but suggests the exchange of six protons of the trialkylphosphine oxides for deuterons. Indeed, high resolution MS confirms the two peaks to be within error identical with the theoretical values expected for the two sodium ion adducts of two hexadeuterated phosphine

oxides (experimental: C, 1217.0208 and D, 1117.0272; theoretical: C, 1217.0213 and D, 1117.0277).

The  $^1\text{H}$  NMR spectra show which protons are exchanged for deuterons, confirming the structures shown in Fig. 4. Before exposure to alkaline solutions, the perfluorohexane solution of the fluorophilic salt **1** showed peaks at 2.63–2.92 ppm (8H, m,  $\text{CH}_2\text{P}$ ) and 3.18–3.44 ppm (8H, m,  $\text{CF}_2\text{CH}_2$ ) (Fig. 5a). Both peaks were relatively broad, which appears to be the result of strong ion aggregation. This is not surprising since the extremely low polarity of fluorosolvents is known to result in exceptionally strong ion pairing.<sup>3,4</sup> After exposure of these solutions to aqueous KOH solution, the two broad signals disappeared, and instead two pairs of signals were observed (see Fig. 5b), *i.e.*, 2.30–2.34 (6H, m,  $\text{CF}_2\text{CH}_2$ ) and 1.78–1.84 (6H, m,  $\text{CH}_2\text{P}$ ), and 1.86–2.00 (2H, m,  $\text{CF}_2\text{CH}_2$ ) and 0.98–1.00 (3H, m,  $\text{CH}_3$ ). The first pair of signals arises from the protons of the two phosphine oxides. The latter two signals correspond to the protons of the two perfluoroalkylethanes  $\text{CH}_3\text{CH}_2\text{R}_{18}$  and  $\text{CH}_3\text{CH}_2\text{R}_{16}$ , which are formed in the hydroxide-induced decomposition of  $(\text{R}_{18}(\text{CH}_2)_2)(\text{R}_{16}(\text{CH}_2)_2)_3\text{P}^+\text{I}^-$ , **1** (see Fig. 4), and indeed match well with the literature values for perfluorohexylethane at 2.0 and 1.1 ppm.<sup>42</sup> When  $\text{NaOH}/\text{D}_2\text{O}$  was used instead of the  $\text{KOH}/\text{H}_2\text{O}$ , only the six protons of the three methylene groups adjacent to  $\text{R}_{16}$  moieties of the phosphine oxide functionality and the three protons of the methyl group in the two perfluoroalkylethanes were observed (Fig. 5c), which also simplified the coupling patterns. The formation of  $\text{R}_{16}\text{CH}_2\text{CD}_3$  shows that the proton–deuteron exchange at the phosphorus-bound methylene groups occurs prior to phosphine oxide formation. In other words, the proton–deuteron exchange is initiated by deprotonation of the tetraalkylphosphonium salt, which is not only stabilized by ylide formation but also the electron-withdrawing perfluoroalkyl group on the carbon atom adjacent to the ylide. Since the two hexadeuterated phosphine oxides and the trideuterated perfluoroalkylethanes  $\text{R}_{16}\text{CH}_2\text{CD}_3$  dominate entirely over species of lesser degree of deuteration, it is evident that the

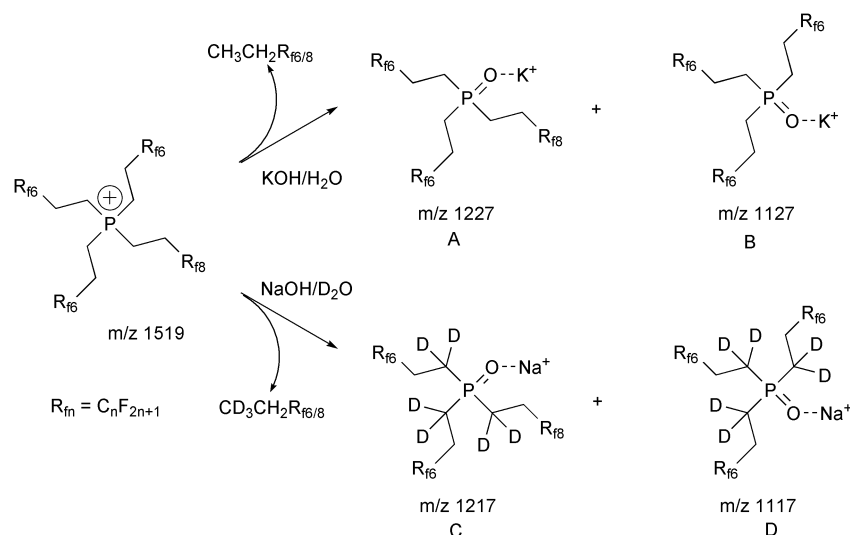
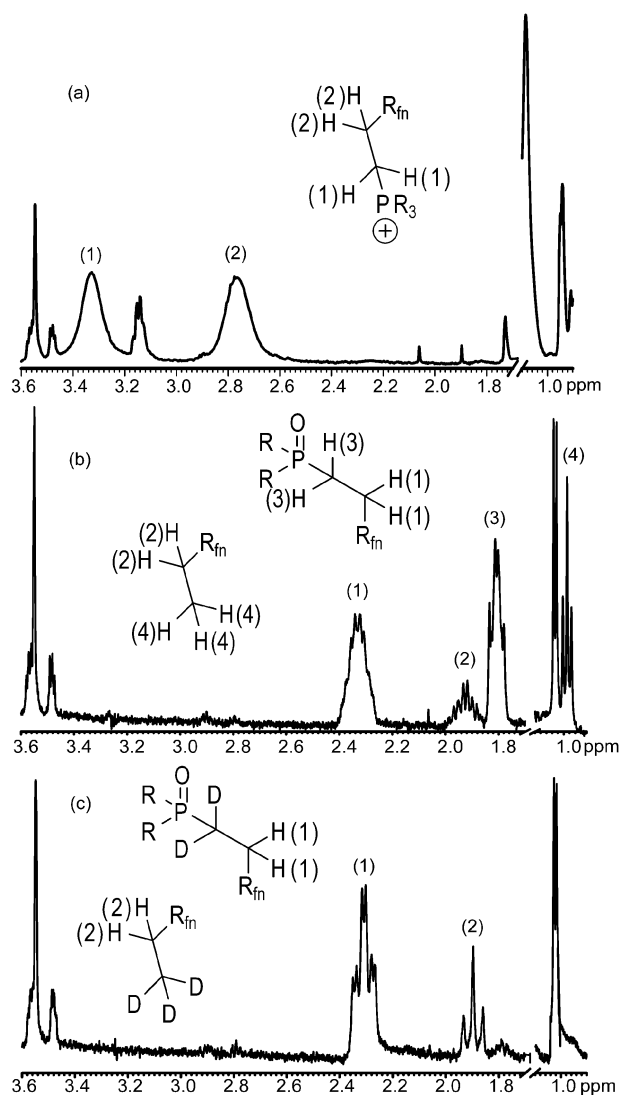


Fig. 4 Decomposition for the fluorophilic cation of salt **1** when exposed to  $\text{KOH}/\text{H}_2\text{O}$  or  $\text{NaOH}/\text{D}_2\text{O}$ .



**Fig. 5**  $^1\text{H}$  NMR spectra of a solution of the fluorophilic salt **1** in perfluoroperhydrophenanthrene, **3**, directly after preparation (a) and after equilibration for 24 h with 1 M KOH in  $\text{H}_2\text{O}$  (b) or 1 M NaOH in  $\text{D}_2\text{O}$  (c). All solutions were diluted five times with perfluorohexanes immediately prior to measurement.

proton–deuteron exchange is much faster than the decomposition of the tetraalkylphosphonium cation to the two phosphine oxides.

## Conclusions

While fluorous membrane ISEs based on the methyltriarylphosphonium salt **2** and ISEs based on the tetraalkylphosphonium salt **1** are suitable for measurements of anions such as  $\text{I}^-$ ,  $\text{NO}_3^-$ ,  $\text{Br}^-$ , and  $\text{Cl}^-$ , and the environmental pollutants perfluorocarboxylates and perfluorosulfonates, only the latter are stable when exposed to anions that are weakly basic. Extended exposure of membranes based on **1** to solutions of pH 13 eventually leads to irreversible damage to the sensors, but brief exposure to highly concentrated solutions of  $\text{OH}^-$  does not impair the anionic response. Formation of a pentavalent species by addition of  $\text{OH}^-$  to

the tetraalkylphosphonium cation could not be observed by  $^{31}\text{P}$  NMR. Hence, this cannot account for the larger than expected  $\text{OH}^-$  interference of membranes containing **1**. Instead, the  $\text{OH}^-$  interference may be related to the accumulation of phosphine oxides in membranes exposed to strongly alkaline solutions and may be the result of dipole–anion interactions between phosphine oxides and anions, as they are similarly known, *e.g.*, for anion–dimethyl sulfoxide adducts.<sup>43,44</sup> Indeed, the slightly higher discrimination of  $\text{I}^-$ ,  $\text{Br}^-$ , and  $\text{NO}_3^-$  with reference to  $\text{Cl}^-$ , as observed in the selectivity experiments, may be the result of an interaction between  $\text{Cl}^-$  and a phosphine oxide. Further studies with ISEs doped with phosphine oxides will be needed to confirm this hypothesis.

For environmental analysis, the high selectivity of the fluorous membranes for perfluorooctanesulfonate and perfluorooctanoate as shown in this contribution is of particular interest.<sup>45–47</sup> Work to exploit the high selectivity in mechanically more robust perfluoropolymer membranes doped with these fluorophilic cationic sites is currently in progress in our laboratories. However, fluorophilic tetraalkylphosphonium ions may be used not only in ion-exchanger electrodes as discussed in this work, but also in ISE membranes that contain in addition to ionic sites an ionophore that selectively binds specific ions.<sup>13–16</sup> Without ionic sites, ISEs based on electrically neutral ionophores do not show any ionic response.<sup>48</sup> Also, the ratio of ion exchanger sites and ionophore plays a crucial role in the control of the selectivity of ion-selective electrodes based on electrically neutral and charged ionophores.<sup>49</sup> Indeed, uses of ionic sites in conventional non-fluorous ionophore-doped membranes by far outnumber the uses of ionophore-free membranes containing only ionic sites. For example, for the years 1999 to 2009, the Science Citation Index lists 197 publications on ISE membranes comprising the common tetrakis(*p*-chlorophenyl)borate as ionic site (introduced as potassium salt), and 184 of these 197 publications discuss ionophore-based sensors. Similarly, the vast majority of the applications of **1** and related tetraalkylphosphonium salts in the still new field of fluorous membrane ISEs are expected to be in combination with fluorophilic ionophores. Moreover, the results presented here will also be relevant to the use of these fluorophilic salts in biphasic catalysis and applications beyond chemical sensing.

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