

## Large Improvement of the Lower Detection Limit of Ion-Selective Polymer Membrane Electrodes

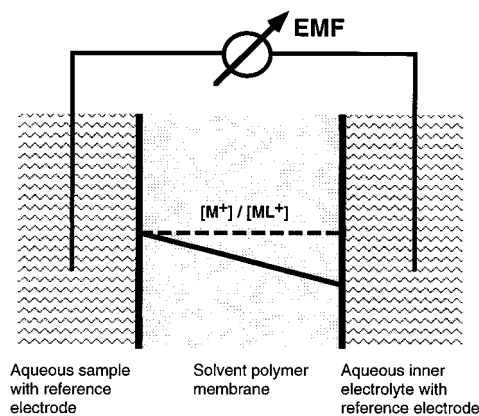
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The lower detection limits of ion-selective polymeric membrane electrodes (ISEs) are in the micromolar range except when sample ion activities are adjusted by using ion buffers, which maintain low and constant activity via superimposed complexation or solubility equilibria.<sup>1</sup> Therefore, they are unsuitable for many important applications. In contrast, detection limits in the picomolar range have been achieved with optical sensors on the basis of similar technology and the same ionophores,<sup>2</sup> suggesting that there is no fundamental reason for the detection limit of analogous ISEs to be worse. Much lower values have indeed been observed when buffering the sample analyte ion,<sup>3</sup> thus supporting the hypothesis that primary ions leaching from the sensor membrane determine the lower limit of the measuring range of the ISE. This also explains the reduction or even lack of response toward highly discriminated ions, which prevents the determination of true selectivity coefficients.<sup>4</sup> Theoretical (Nernstian) response and true selectivity coefficients can, however, be obtained by buffering the primary ion in the sample without influencing the activity of the interfering ion.<sup>5</sup> Recent experiments proved that, even for extremely discriminated ions, Nernstian ISE response is found without buffering the primary ion as long as its contact with the electrode is avoided.<sup>6</sup> Although such experiments are important for understanding the selectivity behavior, they do not contribute to extending the response range in analytical applications.

Since the response of polymeric membrane ISEs is, in essence, a surface phenomenon governed by bulk equilibria,<sup>1b,7</sup> the influence of the aqueous sample composition on concentrations in the bulk membrane is negligible if the electrode response is Nernstian.<sup>8</sup> Therefore, primary ions most likely leach into the sample because, together with their counterions, they are extracted from the internal electrolyte and transported across the membrane. Very recently, Mathison and Bakker showed that such a transport indeed occurs.<sup>9</sup> Their model correctly describes the influence of the composition of the internal electrolyte at high concentrations but does not hold for low ones,



**Figure 1.** Schematic measuring setup and concentration profiles in membrane at steady state. The potential difference between the aqueous solutions is a measure of analyte ( $M^+$ ) activities at the membrane surfaces. In conventional systems (dashed line), slight disturbances induce a flow of  $M^+$  toward the sample, thus biasing its activity at the corresponding membrane surface. This is prevented by the gradient (solid line) brought about in this work.

thus indicating that additional processes must be involved. Moreover, if the detection limit were solely defined by the transport of primary ions from the internal solution, it should be significantly lower for solid contact electrodes. This, however has not been reported so far.

The basic idea of the present work is to prevent primary ions from leaching into the sample by building up a concentration gradient in the membrane (Figure 1). The thereby induced constant flux of primary ions toward the inner compartment prevents their passing into the sample. The concentration gradient is established by choosing an internal electrolyte with low activity of the primary ion and sufficiently high activity of an interfering ion. Since any activity change in the inner compartment would induce a potential change, the low activity of the primary ion was kept constant by using an ion buffer.

The responses of two  $Pb^{2+}$  ISEs with the same membrane<sup>10</sup> but different inner reference systems<sup>11</sup> are shown in Figure 2. With the conventional inner filling solution, the detection limit for  $Pb^{2+}$  is  $4 \times 10^{-6}$  M, no Nernstian response being observed for the discriminated  $Na^+$  since it is not potential determining under these conditions (Figure 2). On the other hand, with the new internal solution, the linear Nernstian response range for  $Pb^{2+}$  is extended to about  $10^{-11}$  M and the detection limit is lowered to  $5 \times 10^{-12}$  M (Figure 2). At the same time, the response toward  $Na^+$  is now Nernstian between  $10^{-2}$  and  $10^{-3}$  M, indicating that  $Na^+$  is the potential-determining ion at these concentrations. Thus, true selectivity coefficients can be determined.

(10) The composition of the membrane was 1.31 wt % (14.5 mmol/kg) of *N,N,N',N'*-tetradodecyl-3,6-dioxaoctanedithioamide (ETH 5435), 0.82 wt % (9.1 mmol/kg) of potassium tetrakis[3,5-bis(trifluoromethyl)phenyl]borate (KTPClPB), 62.5 wt % of bis(2-ethylhexyl) sebacate (DOS), and 35.3 wt % of poly(vinyl chloride) (PVC all Fluka) totaling 368.5 mg dissolved in ca. 2.5 mL of tetrahydrofuran. By casting this solution into a glass ring of  $\varnothing$  53 mm, membranes of ca. 85  $\mu$ m thickness were obtained.

(11) Conventional  $Pb^{2+}$  ISEs were prepared with Philips IS 561 electrode bodies and inner filling solutions of  $5 \times 10^{-4}$  M  $PbCl_2$  and  $5 \times 10^{-2}$  M  $MgCl_2$ . For the construction of the new type of  $Pb^{2+}$  ISEs, the membrane was glued to PVC tubing. The inner filling solution ( $10^{-3}$  M  $Pb(NO_3)_2$  and  $5 \times 10^{-2}$  M ethylenediaminetetraacetic acid disodium salt (EDTA- $Na_2$ )) was in contact with the reference element (Ag/AgCl in 3 M KCl) through a 1 M KCl bridge electrolyte. After the electrodes were conditioned in  $10^{-3}$  M  $Pb(NO_3)_2$  for > 2 d, measurements were made with a Metrohm NET-Titrino 721 at 22–23 °C in successively diluted stock solutions of  $10^{-2}$  M  $Pb(NO_3)_2$  from higher to lower concentrations. End potentials were taken when the drift was  $\leq 0.5$  mV/min (after  $\leq 15$  min for concentrations down to  $10^{-6}$  M and 15–30 min for lower ones). Activities were obtained considering the association of the cations with  $Ac^-$ ,  $OH^-$ , and  $NO_3^-$ ,<sup>13</sup> activity coefficients were calculated according to Debye–Hückel, and diffusion potentials were corrected for according to Henderson.<sup>1</sup>

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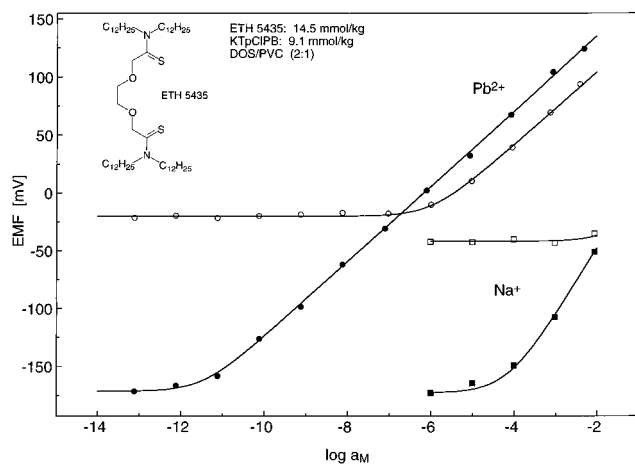
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**Figure 2.** Response of two  $\text{Pb}^{2+}$  ISEs with the same membrane<sup>10,11</sup> but different internal electrolytes (22–23 °C). Conventional (empty symbols): 1:1 mixture of  $10^{-3}$  M  $\text{PbCl}_2$  and 0.1 M  $\text{MgCl}_2$ . New (full symbols): 1 mL of 0.1 M  $\text{Pb}(\text{NO}_3)_2$  in 100 mL of 0.05 M EDTA- $\text{Na}_2$ ; measured pH 4.34. Calculated<sup>13</sup> activities:  $10^{-12}$  M  $\text{Pb}^{2+}$ ,  $10^{-1}$  M  $\text{Na}^+$ .

**Table 1.** Logarithmic Selectivity Coefficients,  $\log K^{\text{pot}}_{\text{PbM}}$ , for a  $\text{Pb}^{2+}$  ISE<sup>10,11,15</sup> with Conventional and Buffered Inner Electrolyte (cf. Figure 2)

ion M	$\log K^{\text{pot}}_{\text{PbM}}$ for $\text{Pb}^{2+}$ ISE with inner solution	
	conventional	this work
$\text{H}^+$	-2.2	-3.5
$\text{Li}^+$	-2.7	-5.1
$\text{Na}^+$	-2.2	-4.7
$\text{K}^+$	-2.2	-4.1
$\text{NH}_4^+$	-2.5	-4.1
$\text{Mg}^{2+}$	-3.6	-9.4
$\text{Ca}^{2+}$	-4.0	-8.6
$\text{Cd}^{2+}$	0.9	0.4
$\text{Sr}^{2+}$	-4.2	-6.7
$\text{Ba}^{2+}$	-4.1	-6.0
$\text{Mn}^{2+}$	-4.1	-5.8
$\text{Co}^{2+}$	-4.3	-6.3
$\text{Ni}^{2+}$	-4.2	-5.9
$\text{Cu}^{2+}$	-0.5	-0.4
$\text{Zn}^{2+}$	-3.7	-5.0

In Table 1, logarithmic selectivity coefficients,  $\log K^{\text{pot}}_{\text{PbM}}$ , are given for both electrodes. It can be seen that most values are drastically lower with the new internal electrolyte, e.g.,  $K^{\text{pot}}_{\text{PbM}}$  for  $\text{Mg}^{2+}$  and  $\text{Ca}^{2+}$  by ca. 5 orders of magnitude, which agrees with the corresponding shift of the lower detection limit. As theoretically expected,<sup>12</sup> the maximal improvement of the logarithmic selectivity coefficient toward monovalent ions is about half that for divalent ions, i.e., 2.5 logarithmic units.

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The concentration of free  $\text{Pb}^{2+}$  in the buffered internal solution, calculated<sup>13</sup> at the measured pH 4.34, is  $10^{-12}$  M and that of  $\text{Na}^+$  (counterion of EDTA) is  $10^{-1}$  M. From  $\log K^{\text{pot}}_{\text{PbNa}} = -4.7$  (Table 1) it is obvious that  $a_{\text{pb}}$  is much smaller than  $K^{\text{pot}}_{\text{PbNa}} \times a_{\text{Na}}^2$  in the internal electrolyte so that  $\text{Na}^+$  is the potential-determining ion at the inner reference side.<sup>12</sup> Hence, it nearly quantitatively replaces  $\text{Pb}^{2+}$  at that boundary so that, at steady state, a concentration gradient of  $\text{Pb}^{2+}$  (and a corresponding inverse one of  $\text{Na}^+$ ) must build up in the membrane. The importance of at least partial displacement of primary ions at the inner membrane surface is also suggested by the fact that when  $\text{Pb}^{2+}$  in the internal electrolyte is buffered to the  $10^{-7}$  M with nitrilotriacetic acid in the presence of ca.  $10^{-3}$  M  $\text{Ca}^{2+}$ , no improvement of the lower detection limit is found.<sup>14</sup> As shown in Table 1,  $\text{Ca}^{2+}$  is strongly discriminated ( $\log K^{\text{pot}}_{\text{PbCa}} = -8.6$ ) so that at the concentrations used,  $\text{Pb}^{2+}$  remains the dominating ion also at the inner membrane side.

The new simple approach described shifts the detection limit to the picomolar region and thus doubles the assessable logarithmic response range from 6 to 12 orders of magnitude. It can be expected that in the future not artifacts but interferences from ions will be the only limiting factor. The method is generally valid for any ion that can be buffered to low activity in the internal electrolyte of the ISE. Similar results have been obtained with  $\text{Ca}^{2+}$  and  $\text{Ag}^+$  ISEs. For  $\text{Ca}^{2+}$ , its concentration in the inner solution was kept low by adding sulfuric acid as an ion buffer. This method could be of interest in miniaturized ISEs. In all cases investigated, not only the detection limit but also the measured selectivities were greatly improved. The robustness of the system and the influence of various membrane parameters are currently being studied. The procedure described allows one to make full use of extremely selective ionophores and opens up new dimensions of ISE applications in trace metal analysis for environmental and biochemical studies by eliminating a fundamental limiting factor.

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(15) Selectivities were measured by the separate solution method<sup>1</sup> in 0.01 M nitrate solutions of  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Mn}^{2+}$ ,  $\text{Co}^{2+}$ ,  $\text{Ni}^{2+}$ ,  $\text{Mn}^{2+}$ ,  $\text{Cu}^{2+}$ ,  $\text{Zn}^{2+}$ , and  $\text{Cd}^{2+}$  buffered to pH 4.7 with a magnesium acetate buffer ( $2.5 \times 10^{-4}$  M  $\text{Mg}^{2+}$ ,  $10^{-3}$  M total  $\text{Ac}^-$ ).