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Perspectives

Selectivity of Potentiometric Ion Sensors

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Selectivities of solvent polymeric membrane ion-selective electrodes (ISEs) are quantitatively related to equilibria at the interface between the sample and the electrode membrane. However, only correctly determined selectivity coefficients allow accurate predictions of ISE responses to real-world samples. Moreover, they are also required for the optimization of ionophore structures and membrane compositions. Best suited for such purposes are potentiometric selectivity coefficients as defined already in the 1960s. This paper briefly reviews the basic relationships and focuses on possible biases in the determination of selectivity coefficients. The traditional methods to determine selectivity coefficients (separate solution method, fixed interference method) are still the same as those originally proposed by IUPAC in 1976. However, several precautions are needed to obtain meaningful data. For example, errors arise when the response to a weakly interfering ion is also influenced by the primary ion leaching from the membrane. Wrong selectivity coefficients may be also obtained when the interfering agent is highly preferred and the electrode shows counterion interference. Recent advances show how such pitfalls can be avoided. A detailed recipe to determine correct potentiometric selectivity coefficients unaffected by such biases is presented.

Ion-selective electrodes (ISEs) belong to the oldest established chemical sensors and are comparatively well understood.^{1–4} Their response characteristics, including selectivities, can be related to basic thermodynamic and kinetic processes.⁴ This not only helps in developing rugged systems but also provides a sound thermodynamic basis for the structure optimization of ionophores in view of sensor applications. Since correctly determined polymeric membrane electrode selectivities are directly related to two-phase equilibria, an important bridge to host–guest chemistry is established. This allows one to accurately predict how an ISE will

respond in a real-world mixed sample. In this paper, we focus on the possible biases of selectivity determinations with solvent polymeric and other liquid membrane ion-selective electrodes containing lipophilic ionophores. This class of ISEs is widely used in clinical and biomedical analysis since the selectivity of these sensors can be tuned by the ion-binding properties of the ionophore and other membrane components. They can also be conveniently miniaturized into sensing arrays and/or microelectrode configurations, making them very attractive devices. Some but not all aspects of the discussion may also apply to other types of ISEs, especially solid-state potentiometric sensors.

ISE responses to only one type of ion can be described with the Nernst equation:

$$\text{EMF} = E_i^0 + (RT/z_i F) \ln a_i \quad (1)$$

where a_i and z_i are the activity and the charge of the measured ion, respectively, and the symbols R , T , and F have their usual meaning. The term E_i^0 incorporates all potential contributions of the measuring cell that are constant for this measurement and is unique for each measured ion. The differences in E^0 obtained for pure solutions with various ions are directly related to the selectivity coefficients (see below). For polymeric membrane electrodes, interferences by other sample ions are mainly dictated by their competitive extraction into the organic phase. Consequently, the response of these ISEs is usually fully predictable from thermodynamic constants, such as the free enthalpies of transfer of the uncomplexed ions from the sample into the membrane and, in the case of ionophore-based systems, the complex formation constant of each ion–ionophore complex in the membrane. Such thermodynamic parameters have become accessible by potentiometric and optical means^{5–8} and can be used to predict the selectivities as a function of the membrane composition. Often, only the selectivity of one sensor with a given membrane composition is of interest, which can be characterized with one thermodynamically founded selectivity coefficient K_{ij}^{pot} for each interfering ion:^{1,2}

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$$K_{IJ}^{\text{pot}} = \exp\{(E_J^0 - E_I^0)z_I F/RT\} \quad (2)$$

Evidently, the selectivity coefficient is a direct function of the differences of the individual potentials extrapolated to 1 M activity for the ions I and J ($E_J^0 - E_I^0$), i.e., the vertical shift between the single calibration curves at 1 M sample activities (see Figure 1A, left). Correct K_{IJ}^{pot} values are obtained from adequate, unbiased E^0 measurements for each ion. Selectivity coefficients can then be conveniently used to predict response functions in mixed samples.^{9,10}

THE PROBLEMS

In recent years, a number of selectivity measures have been suggested as alternatives for the classical potentiometric selectivity coefficients K_{IJ}^{pot} . Several reasons have led to the formulation of those alternate approaches. One of the problems is that K_{IJ}^{pot} was originally introduced with the empirical Nicolsky–Eisenman equation,^{11–13} which is now known to be incorrect when two ions of different charges significantly contribute to the emf.^{9,14}

$$\text{EMF} = E_I^0 + (RT/z_I F) \ln(a_I + \sum K_{IJ}^{\text{pot}} a_J^{z_I/z_J}) \quad (3)$$

Another point that led to confusion is that K_{IJ}^{pot} has different dimensions for different charges of the interfering ion J. A direct comparison of the numerical values of two selectivity coefficients K_{IJ}^{pot} and K_{IK}^{pot} is not meaningful if the charges z_I and z_K are different. A fast rough estimate of the interference is, however, always possible by comparing the sample activity of the primary ion, a_I , with the very simple expression $K_{IJ}^{\text{pot}} a_J^{z_I/z_J}$ (see eq 3). For example, interferences are comparable for a divalent ion-selective electrode in the presence of 10^{-2} M monovalent or divalent interfering ions with selectivity coefficients of 10^{-1} or 10^{-3} , respectively. Note that the extent of interference always depends on the ion activities if the charges of the primary and interfering ions are different. This is a direct consequence of the dependence of the electrode slope on the ion charges (see eq 1). Any selectivity measure that attempts to avoid this will inevitably depend on the sample composition.

The traditional procedures to assess K_{IJ}^{pot} values are the separate solution method (SSM) and the fixed interference method (FIM).^{15,16} Numerous problems have also arisen for experimental reasons that caused the experimentally determined K_{IJ}^{pot} values to differ from the thermodynamically founded ones. This may occur if the calculation of these K_{IJ}^{pot} values is not based on measurement conditions under which either only the primary or the interfering ion is potential-determining. In practical terms,

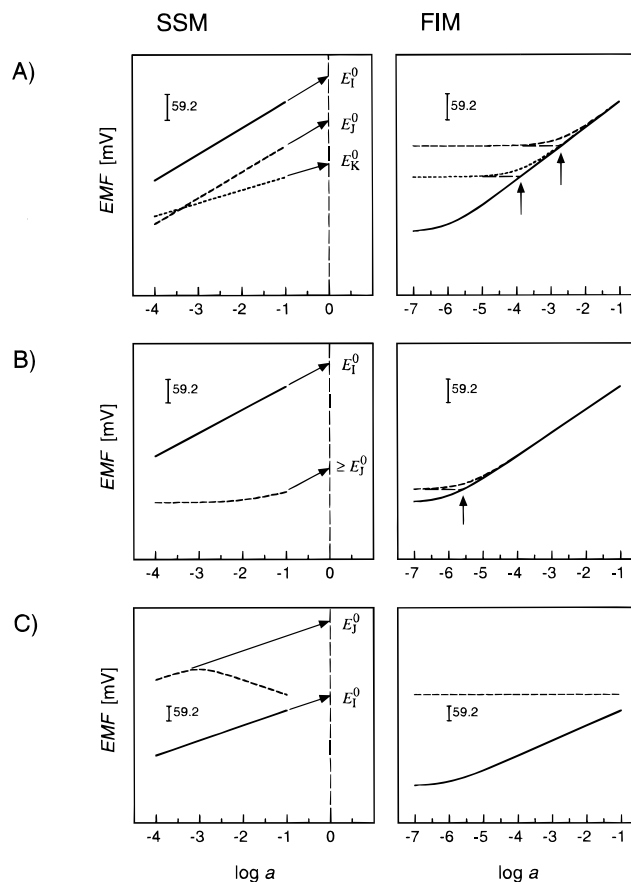


Figure 1. Representation of the separate solution method (SSM, left) and fixed interference method (FIM, right) under (A) ideal and (B, C) nonideal conditions. Solid lines, response to primary ion; dashed and dotted lines, monovalent and divalent interfering ions, respectively. With SSM, the selectivity coefficient is determined from the E^0 values, which can be obtained from extrapolation to $\log a = 0$. In the case of the FIM, information about the electrode slope for the response of the interfering ion should be obtained in additional experiments. The experiment can be mainly biased by (B) the lower or (C) the upper detection limit. For situation (B), only a maximum selectivity coefficient can be reported; the highest possible activity of the interfering ion should be used.

this means that in most cases the emf response to the interfering ion was not measured in a concentration range in which the electrode responds Nernstian to that ion. Although the experimental validation of this condition is quite simple, its importance has not been realized in many cases and has, unfortunately, never been officially recommended by IUPAC.^{15–17} In an overwhelming number of cases, this condition is only violated for weakly interfering ions and the reported K_{IJ}^{pot} values are high limits; i.e., the reported sensing selectivities are too pessimistic. But erroneous values have occasionally also been reported because the primary or a strongly interfering ion did not show a Nernstian response. Of course, if K_{IJ}^{pot} values are biased, their numerical values will depend on the experimental conditions, as correctly pointed out in the literature.^{17,18}

Because of the above reasons it has been erroneously inferred that K_{IJ}^{pot} in itself is an inadequate measure of selectivity. However, it is now well documented in the literature that this

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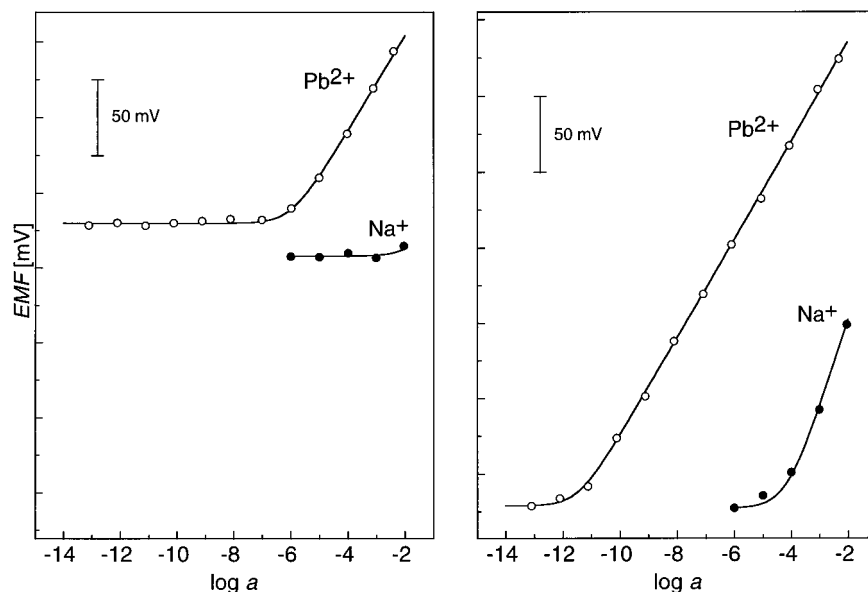


Figure 2. Elimination of the low detection limit bias with SSM.²² Left: a classical SSM experiment results in a very high Na^+ detection limit, where Pb^{2+} ions that leach from the membrane dictate the response. Right: the bias is eliminated by introducing a Pb^{2+} flux in the direction of an EDTA-containing inner electrolyte, resulting in a Nernstian response slope for Na^+ . The resulting selectivity coefficient is unbiased and is with $\log K_{\text{Pb,Na}}^{\text{pot}} = -4.7$ much smaller than the value -2.2 obtained from the classical measurements (left side).

conclusion is false.^{2,4,9,19–22} As shown in eq 2, $K_{\text{IJ}}^{\text{pot}}$ is defined on a theoretical basis without utilizing the empirical Nicolsky–Eisenman equation. Theoretical models are now available on how to use correctly determined selectivity coefficients to describe emf responses to mixed solutions for which the Nicolsky–Eisenman equation fails.^{9,10} In the following, the most typical biases in the determination of selectivity coefficients are further highlighted and various possibilities for their elimination are outlined.

FREQUENT BIASES WITH THE SEPARATE SOLUTION METHOD

The separate solution method for assessing selectivity coefficients is in essence based on eq 2 and the determination of the potentials E_{I}^0 and E_{J}^0 , by extrapolating the response functions for the ions I^z and J^z to 1 M activities (eq 4).

$$K_{\text{IJ}}^{\text{pot}} = \frac{a_{\text{I}}}{a_{\text{J}}^{z_{\text{I}}/z_{\text{J}}}} \exp\left\{\frac{E_{\text{J}} - E_{\text{I}}}{RT} z_{\text{I}} F\right\} = \exp\left\{\frac{E_{\text{J}}^0 - E_{\text{I}}^0}{RT} z_{\text{I}} F\right\} \quad (4)$$

The obtained $K_{\text{IJ}}^{\text{pot}}$ values are equal to the thermodynamically defined ones as long as the response slopes of all ions in question are Nernstian (Figure 1A, left). The most frequent error arises from the fact that the response to a weakly interfering ion is also influenced by the primary ion leaching from the membrane (Figure 1B, left). In the absence of any precautions, the primary ion activity at the membrane surface is typically in the 10^{-6} – 10^{-7} M range. Consequently, if measurements are made at $a_{\text{I}} = 10^{-2}$ M, the best selectivity coefficients found with this method are for

monovalent primary ions on the order of $\log K_{\text{IJ}}^{\text{pot}} = -4$ ($z_{\text{I}} = 1$) to -5 ($z_{\text{I}} = 2$) and for divalent primary ions $\log K_{\text{IJ}}^{\text{pot}} = -2$ ($z_{\text{I}} = 1$) to -4 ($z_{\text{I}} = 2$). In reality, such values are upper limits rather than true selectivity coefficients. They depend, in contrast to the ideal case (Figure 1A, left), on the interfering ion activity used. To obtain the most representative limiting value, the calculation of $K_{\text{IJ}}^{\text{pot}}$ should be based on the emf obtained with the highest possible concentration of the interfering ion, which is not necessarily equal to the activity of the primary ion (see eq 4). A practical example is shown in Figure 2. The traditional selectivity measurement with an ISE, whose detection limit is given by leaching of the primary ion from the membrane, results in $\log K_{\text{Pb,Na}}^{\text{pot}} = -2.2$. When leaching is eliminated, $\log K_{\text{Pb,Na}}^{\text{pot}} = -4.7$ is obtained, which is the true selectivity coefficient, as indicated by the close to Nernstian slope obtained also for the interfering Na^+ .²² In this case, the bias through leaching was eliminated by using an electrode with an appropriate inner solution. Other possibilities are to use membranes that had not been in contact with primary ions before measuring all interfering ions¹⁹ or, in some cases, the application of samples containing ion buffers that complex the primary but not the interfering ions.²¹ The differences found between unbiased and biased selectivity coefficients can be up to 6 and 11 orders of magnitude for monovalent and divalent ion-selective electrodes, respectively. The new techniques revealed that unbiased selectivity coefficients are in many cases much smaller than had been assumed in the original papers and that values of $\log K_{\text{IJ}}^{\text{pot}} < -10$ are not uncommon.^{7,19–21,23}

Unbiased selectivity coefficients in combination with known detection limits and an appropriate response model can generally be used to correctly predict the responses of ISEs to real-world samples at any concentrations of primary and interfering ions. In contrast, biased selectivity coefficients are only useful to predict

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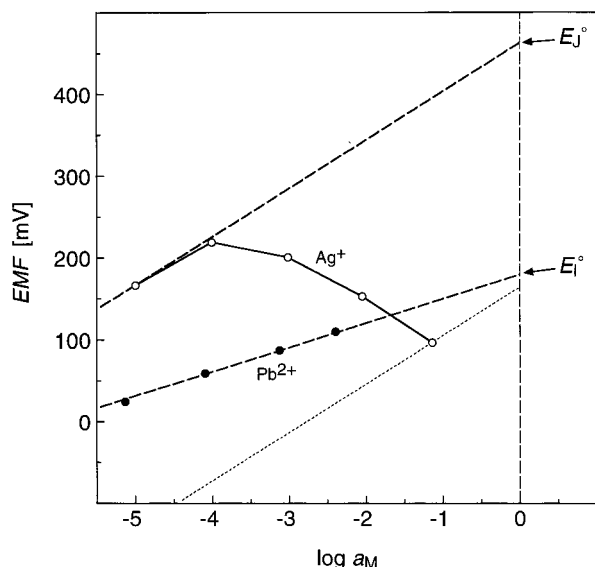


Figure 3. The bias from the upper detection limit with SSM.²³ Sometimes, either the interfering or analyte ion shows a slope with sign reversal at high concentrations. This originates in coextraction of sample anions and cations from the sample into the ISE membrane. Selectivity coefficients are correctly determined from the Nernstian response portions of each calibration curve. Otherwise, the resulting values are highly inaccurate.

emf responses under very specialized conditions. Moreover, electrodes based on highly selective membranes can be optimized to exhibit low detection limits, thereby eliminating the bias that has caused the evaluation of faulty selectivity coefficients in the first place. It is thus evident that proper selectivity determinations are not only of academic interest but of real utility to the practical analytical chemist.

Occasionally, problems with the slopes of highly preferred ions occur. As a consequence of too strong complexes, the membrane loses its permselectivity and the preferred ion is extracted together with its counterion into the membrane.²⁴ This may induce response slopes with reversed signs, i.e., negative slopes for cations (Figure 1C, left). If potential readings from this portion of the response curve are used to calculate K_{IJ}^{pot} (dotted line in Figure 3), the high preference of such ions is seemingly reduced and the experimentally determined K_{IJ}^{pot} value depends on the concentration used. However, true selectivity coefficients can be obtained from the Nernstian portion of the response curve at lower activities (dashed line in Figure 3).²³ Such biases can lead to errors of up to 8 orders of magnitude.²³

FREQUENT BIASES WITH THE FIXED INTERFERENCE METHOD

The fixed interference method is in essence also based on the determination of E_I^0 and E_J^0 from measurements where only one of the ions is potential determining. In practice, incremental amounts of primary ions are added to a solution containing a constant concentration of an interfering substance until a Nernstian response slope to the primary ion is observed. Incremental dilution with a background interference solution is a convenient alternate approach since it may be performed with automatic

diluters.^{7,25} This linear response region is extrapolated to the emf for the background interference only (see arrows in Figure 4), and the primary ion activity $a_I(\text{DL})$ at this detection limit is, together with the interfering ion activity in the background $a_J(\text{BG})$, inserted into the following equation:

$$\log K_{IJ}^{\text{pot}} = \log a_I(\text{DL}) / a_J(\text{BG})^{z_I/z_J} \quad (5)$$

This approach is formally identical to extrapolating the emf values to 1 M activities (see eq 4) if Nernstian electrode slopes are observed. Ideally, therefore, SSM and FIM give identical results.

In the past, the fixed interference method has been preferred since it more closely mimics a practical application of the sensor.¹⁵ An important drawback, however, is that the response slope for the interfering ion has traditionally not been determined. Consequently, the most common error in the determination of selectivity coefficients according to FIM involved again a bias from the lower detection limit of the ISE. It is therefore important to compare the response curve from the actual selectivity measurement with a calibration curve for the primary ion without background interference. The detection limits of the two experiments must be different by at least 1 order of magnitude to indicate that such a bias is absent. Otherwise, as with SSM, only a conservative upper limit for the selectivity coefficient is obtained and must be reported as such (see Figure 1B, right). Perhaps the most adequate method to confirm the absence of such an experimental bias is illustrated in Figure 4.⁷ After the established FIM measuring protocol is performed, each background interference solution is incrementally diluted with water. As with SSM, Nernstian electrode slopes confirm that a bias is absent.

In Figure 1C, right, it is shown that FIM also fails when the interfering agent is highly preferred by the electrode and the electrode shows counterion interference under the conditions used. In such a situation, the FIM protocol would never show a Nernstian slope to the primary ion, and a dilution of the background solution would show a sign reversal of the electrode slope. As with SSM (see Figure 1C, left), a more dilute background solution must be chosen in order to observe a Nernstian response behavior for the interferent alone.

It must be emphasized that the fixed interference method utilizes only the potential values of the calibration curve where the electrode shows a Nernstian response to either ions I or J. It is of course feasible to analyze the entire potential region where the electrode responds to both ions simultaneously for determining selectivity coefficients. As mentioned above, the empirical Nicolsky–Eisenman eq 2 may only be used for this purpose if both ions have an identical charge and no experimental biases such as the ones discussed above exist. For ions of different charge, an improved model is available that utilizes the same selectivity coefficients K_{IJ}^{pot} (see Figure 5, upper solid line).^{9,10} The Nicolsky–Eisenman equation is not capable of describing this response region and leads to higher predicted potentials for the monovalent interfering ion (Figure 5, upper dotted line). However, at low levels of interfering ions local concentrations at

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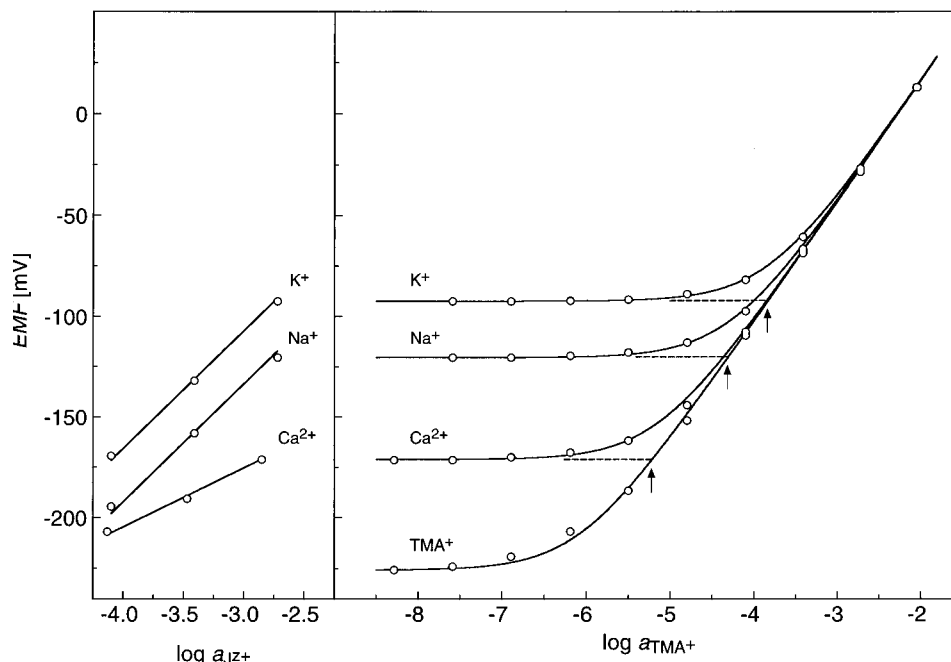


Figure 4. Recommended use of the FIM.⁷ The concentration of the analyte ion tetramethylammonium (TMA^+) is varied in a background of a chosen interference (right). The cross section of the two linear portions (indicated by arrows) is used to determine the selectivity coefficient. Any bias from the lower detection limit can be revealed by (1) ensuring that the background interference induces a potential that is significantly higher than without added interference (right) and/or by (2) performing a successive dilution of the background interference solution with water to confirm Nernstian slopes for that ion (left).

the sensing electrode surface are often perturbed by zero-current membrane fluxes.^{23,26} Figure 5, bottom curves, shows how a dilute calcium background yields a sodium response curve that is biased by sodium ion flux into the sample and, as a result, more closely matches the response predicted by the Nicolsky–Eisenman equation than that from the new, consistent model.^{9,27} However, a $K_{\text{IJ}}^{\text{pot}}$ value determined by the fit of the Nicolsky–Eisenman equation to such a curve is biased. Therefore, also in this case it is important to verify that the interfering ion alone is potential determining in dilute solutions. As mentioned above, a number of methods are available to at least partly eliminate ion fluxes that can influence ISE calibration curves.

THE MATCHED POTENTIAL METHOD

As shown above, when correctly applied, the two methods SSM and FIM result in identical values of selectivity coefficients that are constant for a membrane of given composition and, together with the appropriate equations, have the best possible predictive abilities for responses to mixtures of the ions. However, many biased values have been reported in the literature. Furthermore, to roughly estimate the interference caused by two ions of different charges, the numerical values of $K_{\text{IJ}}^{\text{pot}}$ can only be compared upon multiplication with the activity of the interference, $a_{\text{J}}^{z_{\text{J}}/z_{\text{I}}}$. These two facts are the main reasons for the recent revival of another selectivity measure, the selectivity factor, $k_{\text{IJ}}^{\text{MPM}}$, determined according to the matched potential method.^{17,28}

As illustrated in Figure 6, the $k_{\text{IJ}}^{\text{MPM}}$ value is determined as follows: First, the potential change upon increasing the primary analyte activity by an increment of Δa_{I} in a starting solution is measured. Interfering ions are then added to an identical starting solution until the same potential change is observed. The selectivity factor $k_{\text{IJ}}^{\text{MPM}}$ is then obtained as the ratio of the changes in the

activity of the analyte, Δa_{I} , and interfering ion, Δa_{J} .^{17,28}

$$k_{\text{IJ}}^{\text{MPM}} = \Delta a_{\text{I}} / \Delta a_{\text{J}} \quad (6)$$

As pointed out by its supporters, the matched potential method can be applied to ISE responses of any type because it is not bound by any model assumptions. However, as a consequence, selectivity factors determined with MPM in general lack a predictive ability about the emf measured with solutions other than those for which it was determined.²⁹ The method is applicable in cases of non-Nernstian responses, although highly discriminated interfering cations sometimes induce negative potential changes that lead to useless selectivity factors.²⁰ Ordinarily, the sign of a $\log k_{\text{IJ}}^{\text{MPM}}$ value shows whether the ISE responds more strongly to the primary or to the interfering ion at the concentrations at which they were measured. On the other hand, the $k_{\text{IJ}}^{\text{MPM}}$ values are highly concentration dependent in the case of primary and interfering ions of different valencies (see Figure 6) and even change sign where the separate calibration curves for the two ions intersect. Therefore, the term “factor” instead of “coefficient” and the lowercase letter k instead of the capital letter K in the symbol $k_{\text{IJ}}^{\text{MPM}}$ are used here to stress that, in contrast to $K_{\text{IJ}}^{\text{pot}}$, values of $k_{\text{IJ}}^{\text{MPM}}$ in general depend on the experimental conditions. Importantly, when reported without the concentrations for which they were measured, as it is unfortunately often done by users of this method, $k_{\text{IJ}}^{\text{MPM}}$ values lose any meaning.

Values of $k_{\text{IJ}}^{\text{MPM}}$ gain predictive abilities when the primary and interfering ions give Nernstian responses. Then, $k_{\text{IJ}}^{\text{MPM}}$ and $K_{\text{IJ}}^{\text{pot}}$

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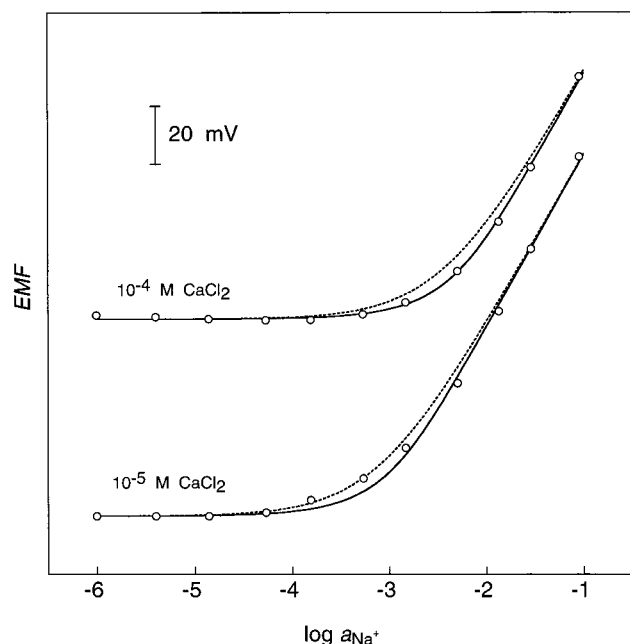


Figure 5. Influence of deviations of the phase boundary activities from the bulk sample composition on the apparent mixed sample response behavior around the detection limit, as shown here for a Na^+ -selective electrode with two different Ca^{2+} background concentrations.^{9,27} While the measurement with higher Ca^{2+} background is well predicted by theory (solid line), the one with a dilute background is better described with the empirical Nicolsky–Eisenman equation because not the interference (Ca^{2+}) but the primary ion leaching from the membrane determines the emf at low sample activities. Fitting the Nicolsky–Eisenman equation to such a response inevitably leads to erroneous selectivity coefficients.

values are directly comparable if the primary and interfering ion have equal charge (see Figure 6). Interestingly, under ideally unbiased measurement conditions, k_{ij}^{MPM} values are also thermodynamically meaningful when they are determined near the true detection limit, i.e., in a concentration range where both the primary and interfering ions significantly contribute to the emf (cf. Figure 6). However, complications arising from a bias related to the lower detection limit may falsify k_{ij}^{MPM} from such measurements and are hard to detect unless the occurrence of a Nernstian response slope at higher activities for the interfering ion is verified (see Figure 4 and preceding section on FIM). Moreover, if the primary and interfering ions have different charges, the k_{ij}^{MPM} values are concentration dependent even if determined in the range of Nernstian responses (see Figure 6). Interconversion of k_{ij}^{MPM} values measured in different laboratories for different concentration steps is possible but more cumbersome than the estimation of interferences by using K_{ij}^{pot} in case of ions of different charges.

In view of these limitations of k_{ij}^{MPM} , we cannot recommend the matched potential method for electrodes that respond Nernstian to primary ions. The method is justifiable for some naughty classical electrodes that, despite appropriate measures, do not provide Nernstian responses to the primary ion and for sensors responding according to other principles, such as Severinghaus-type or enzyme electrodes. However, calibration curves provide much more information than a single value of k_{ij}^{MPM} in such cases.

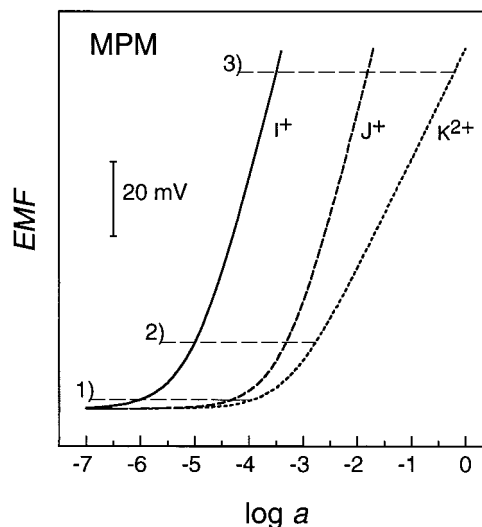


Figure 6. Representation of the matched potential method. Under ideal conditions, the method gives identical selectivity factors for interfering ions that have the same charge as the analyte ion. In this calculated example, for primary ion activity changes of 10^{-6} , 10^{-5} , and 10^{-4} M (marked with 1–3), identical selectivity factors $\log k_{ij}^{\text{MPM}} = -1.69$ are obtained, which is equal to the respective K_{ij}^{pot} value. For a divalent interference K^{2+} , corresponding concentration-dependent $\log k_{ik}^{\text{MPM}} = -2.08$, -2.23 , and -3.28 result, which do not directly compare with the appropriate selectivity coefficient $\log K_{ik}^{\text{pot}} = -3.38$.

WHAT TO DO? A RECIPE FOR EXPERIMENTALISTS

Both traditional methods, i.e., SSM and FIM, can be used to obtain selectivity coefficients, K_{ij}^{pot} , that are unbiased, i.e., equal to the thermodynamically defined ones. The prerequisite is that the selectivity coefficients are determined under conditions where the response to each of the ions in the investigated activity range is Nernstian; i.e., the respective ion is potential determining. Recommendations for the specific procedures are given below.

Separate Solution Method. (1) The calibration curve for the primary ion is measured. If its slope is close to Nernstian, E_1^0 is calculated by extrapolating the response to $a_1 = 1$ M. This is done by using the theoretical slope from measured values at different activities, to obtain the mean and standard deviation. A significantly smaller slope than theoretical or a slope of the opposite sign than expected may occur at high activities as a consequence of counterion interference. In such a case, the portion of the calibration curve at lower activities may be used if it is close to Nernstian. If no Nernstian portion of the response to the primary ion is obtained, no selectivity coefficient should be determined. In such a case, it is best to report the calibration curve to represent the selectivity.

(2) The calibration curves for the interfering ions in question are measured. If they are Nernstian, the mean and standard deviation of the individual E_j^0 values are determined as above and K_{ij}^{pot} is calculated with eq 4. Significantly lower than Nernstian slopes usually indicate that not only the interfering ion J but the also the primary ion I leaching from the membrane is potential determining. In such cases, the experimental bias has to be eliminated by using one of the methods given below under (3) or maximal limiting values of K_{ij}^{pot} can be calculated from the measurement at the highest activity of the interfering ion (see Figure 1B, left). Apparently super-Nernstian slopes for the interfering ion can often be eliminated by measuring at high

concentrations. If no Nernstian portion of the electrode response curve is obtained, it is best to report the calibration curve to characterize the ISE.

(3) The bias caused by ions leaching from the membrane can be eliminated (a) by using appropriate inner reference electrolyte solutions that prevent leaching,²³ (b) by measuring calibration curves with membranes that had not been in contact with the primary ions, starting with the most discriminated ions in sequence of decreasing discrimination,¹⁹ or (c) by using complexing agents for the primary ions in the sample.²¹

Fixed Interference Method. (1) The calibration curve for the primary ion is measured without additional background electrolyte and the lower detection limit is determined from its two linear portions (see Figure 1, right).

(2) The calibration curve for the primary ion is measured in the presence of an interfering ion. The lower detection limit is determined and should be significantly different from the detection limit observed under (1). The detection limit is ideally determined by the added interfering ion alone. This assumption must be scrutinized by subsequent dilution of the sample with water, whereupon a Nernstian response to the interfering ion must be observed (see Figure 4). Otherwise, only limiting maximum values of the selectivity coefficients may be reported.

(3) The selectivity coefficients or their upper limits are calculated according to eq 5.

CONCLUSIONS

Potentiometric selectivity coefficients, as defined already in the 1960s, offer the best possibility to characterize the selectivity

behavior of ISEs. They not only have the best predictive capabilities but they also can be directly related to thermodynamic data of two-phase equilibria. The practically observed response function can then be satisfactorily described with dedicated response models that, however, differ from the traditionally used empirical Nicolsky–Eisenman equation. Except in special situations, there is no need for alternative measures. The basic methods to determine selectivity coefficients are the same as those originally proposed by IUPAC in 1976. However, as described in this report, several precautions are needed to obtain meaningful data. With unoptimized sensors characterized by very high membrane selectivities but unsatisfactory lower detection limits, for example, obtained selectivity values may otherwise be wrong by 10 or more orders of magnitude. In special cases, the suggested methods do not lead to useful values but then also the alternative measures have little predictive value. The best characterization of sensors in such situations is to publish the response curves for the individual ions.

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