

# Insights into Primary Ion Exchange between Ion-Selective Membranes and Solution. From Altering Natural Isotope Ratios to Isotope Dilution Inductively Coupled Plasma Mass Spectrometry Studies

Agnieszka Anna Krata, Emilia Stelmach, Marcin Wojciechowski, Ewa Bulska, Krzysztof Maksymiuk,\* and Agata Michalska\*

Cite This: *ACS Sens.* 2020, 5, 3930–3938

Read Online

ACCESS |

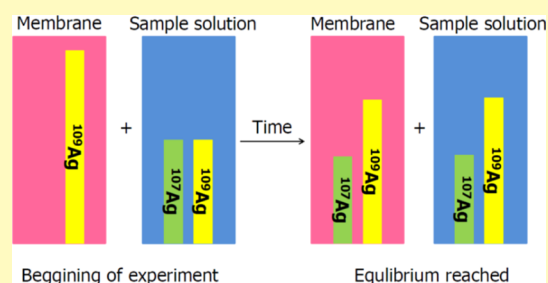
Metrics & More

Article Recommendations

Supporting Information

**ABSTRACT:** Although ion-selective electrodes have been routinely used for decades now, there are still gaps in experimental evidence regarding how these sensors operate. This especially applies to the exchange of primary ions occurring for systems already containing analyte ions from the pretreatment step. Herein, for the first time, we present an insight into this process looking at the effect of altered ratios of naturally occurring analyte isotopes and achieving isotopic equilibrium. Benefiting from the same chemical properties of all isotopes of analyte ions and spatial resolution offered by laser ablation and inductively coupled plasma mass spectrometry, obtaining insights into primary ion diffusion in the preconditioned membrane is possible. For systems that have reached isotopic equilibrium in the membrane through ion exchange and between the membrane phase and the sample, quantification of primary ions in the membrane is possible using an isotope dilution approach for a heterogeneous system (membrane–liquid sample). Experimental results obtained for silver-selective membrane show that the primary ion diffusion coefficient in the preconditioned membrane is close to  $(6 \pm 1) \times 10^{-9} \text{ cm}^2/\text{s}$ , being somewhat lower compared to the previously reported values for other cations. Diffusion of ions in the membrane is the rate limiting step in achieving isotopic equilibrium between the ion-selective membrane phase and sample solution. On the contrary to previous reports, quantification of silver present in the membrane clearly shows that contact of the membrane with silver nitrate solution of concentration  $10^{-3} \text{ M}$  leads to pronounced accumulation of silver ions in the membrane, reaching almost 150% of ion exchanger amount. The magnitude of this effect increases for higher concentration of the electrolyte in the solution.

**KEYWORDS:** ion-selective membrane, isotope dilution, ICP–MS, laser ablation, altered isotope ratio, isotopic equilibrium, concentration profile



**I**on-selective membrane (ISM)-based sensors are established tools for chemical analysis. Theoretical description of their operation has been developed, and the routine applications protocols are available. Operation of ISMs requires ion exchange between the membrane and the sample and transport of ions within the recognition element.

Visualization/quantification of ion incorporation into relatively thin polymeric layers as ISMs is complicated. Different experimental approaches have been proposed for this purpose, typically addressing as prepared, that is, analyte ion free membranes. ISMs were replaced by a stack of thin membranes that were analyzed separately,<sup>1</sup> and scanning electrochemical microscopy was used to visualize the diffusion layer at the aqueous phase boundary of ion-selective electrodes.<sup>2–4</sup> Electrochemical methods, however, give information (only) about the membrane as the whole system without spatial resolution.<sup>2–4</sup> The phenomena related to the membrane surface have been studied using Fourier-transform

infrared spectroscopy with attenuated total reflection (FTIR–ATR)<sup>5</sup> and second harmonic generation method.<sup>6</sup> In the early years of ISMs, incorporation of ions to the membrane phase (without spatial resolution) was followed using radiotracers.<sup>7–9</sup> More information related to ion exchange and ion transport through ISMs can be obtained using VIS spectroscopic methods.<sup>10–15</sup> However, this approach can be applied only for membranes containing chromoionophores, that is, for systems of different compositions compared to those applied in potentiometry. Moreover, the customized setup is required for

Received: August 1, 2020

Accepted: November 16, 2020

Published: December 10, 2020

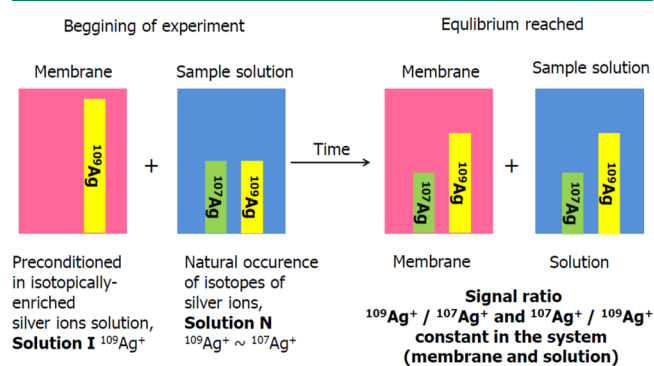


these experiments, too. Alternative instrumental methods are used to study the ISM/transducer interface (in all-solid state sensors) including neutron reflectometry, secondary ion mass spectrometry (MS), small-angle neutron scattering, and others.<sup>16–21</sup>

A few years ago, we proposed the application of laser ablation with inductively coupled plasma mass spectrometry (LA ICP–MS) to study ion transport, including the determination of ion-diffusion coefficients in ISMs.<sup>22</sup> This method provides insights into the changes of contents of different elements present in the membrane in a single experiment with minute spatial resolution.<sup>22–30</sup> The important advantage of this approach is the possibility of studying membranes of exactly the same composition, as in electrochemical experiments. Thus, incorporation of ions into the (as prepared) membrane can be followed as change in the contents of individual isotopes of the analyte. LA ICP–MS was used also to visualize the impact of the electrochemical experiment performed on ISMs or phenomena occurring between the membrane and the transducer used.<sup>22–30</sup> Using this approach, we have shown that conditioning in  $10^{-3}$  M solution results in an equilibrated membrane with a mole amount of primary ions equal to that of the ion exchanger present in the membrane.<sup>24,30</sup> It was also shown that in extreme coextraction of primary ions from the sample leads to membrane contents nearly 6 times higher compared to mole amount of the used ion exchanger.<sup>30</sup> However, the absolute content of primary ions in the preconditioned membrane was an estimated value only, related to the amount of ion exchanger; because of the lack of standards, the absolute amount cannot be given. Moreover, this approach is not helpful to look at processes related to primary ion exchange between the sample solution and preconditioned membrane. Although ICP–MS addresses individual isotopes as analytes, typically all solutions used in electrochemical experiments contain the primary ions, although in different concentrations, but in the same natural ratio of isotopes. Thus, to the best of our knowledge, exploring the isotope ratio for tracing the phenomena of the exchange of ions between the fully preconditioned ISM and solution of sensor primary ions has not been presented before.

We address this problem for the first time by altering the ratio of naturally occurring isotopes and looking at processes of achieving isotopic equilibrium in the membrane and between the membrane phase and solution. Isotopic equilibrium prevailing in the system allows the application of isotope dilution (ID) ICP–MS for in situ quantification of primary ions in the membrane phase. The ID approach is benefiting from the ICP–MS insights into changes in the isotope composition in the studied systems at the isotopic equilibrium. ID ICP–MS looks at changes in the isotope ratio resulting from contact of the sample and the standard containing the same element, but of different isotopic composition. This primary method of measurements offers high metrological quality: excellent accuracy and precision.<sup>31–36</sup> In the direct ID ICP–MS, a known amount of isotopically enriched standard (spike) is added to the analyzed sample, whereas, in the reverse mode, one natural isotope abundance standard is added to the isotopically enriched solution.<sup>37</sup> ID ICP–MS has been successfully used for different analytical purposes including complex matrices and speciation analysis,<sup>38–43</sup> yet its application to heterogeneous systems (e.g., solid state sample in contact with liquid standard) is limited, to the best of our

knowledge. For heterogeneous samples, the process of reaching isotopic equilibrium offers a unique opportunity to study the exchange of ions between the solid sample and solution, provided that initially they contain the same ions, but different ratios of natural (nonradioactive) isotopes. In particular, it gives a unique opportunity to look into the processes occurring during contact of the sample—ISM containing primary ions and a liquid standard—sample solution containing primary ions. The contact of the membrane pretreated in a solution of a certain isotope ratio and transferred to a solution of other ratio of isotopes of the same analyte can be followed with a spatial resolution of the membrane phase using, for example, laser ablation ICP–MS, giving insights into ions diffusion in the membrane phase. Thus, typically obscured processes of ion transport in primary ions' saturated membrane are shown in Figure 1. To the best



**Figure 1.** Schematic representation of the experimental idea of ID quantification.

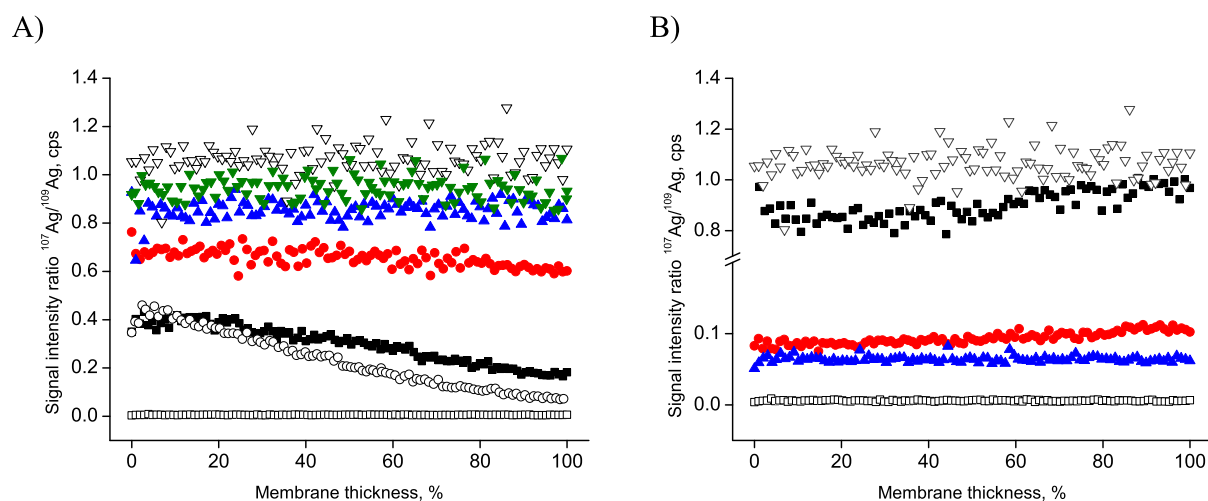
of our knowledge, this effect was not directly shown before; however, different indirect proofs of its occurrence are available, for example, ref 29. It is rational to expect that the ions' diffusion in the ISM is the rate-limiting step in reaching isotopic equilibrium in the system as the ion diffusion coefficients for plasticized PVC are typically close to  $10^{-8}$   $\text{cm}^2/\text{s}$ ,<sup>14,22</sup> whereas ion exchange at the interface is usually a fast process,<sup>44</sup> as observed for membrane saturation with primary ions.

As a model system, silver-selective membranes of the same composition as in electrochemical experiments were used. The choice of this system is justified by the reported changes in the potentiometric performance of the sensors which can be attributed to coextraction and generally lead to non-Nernstian performance of the sensor and increased contents of primary ions in the membrane.<sup>26,29,30</sup> There are two naturally occurring stable isotopes of silver of similar abundances and isotope ratios close to one (48.16% of  $^{109}\text{Ag}$  and 51.84% of  $^{107}\text{Ag}$ ), whereas commercially available isotopically enriched solution contained 99.41% of  $^{109}\text{Ag}$ .

## EXPERIMENTAL SECTION

**Reagents.** Doubly distilled and freshly deionized water (resistivity 18.2 M $\Omega$  cm, Milli-Q plus, Millipore, Austria) was used throughout this work.

Tetrahydrofuran (THF), poly(vinyl chloride) (PVC), bis(2-ethylhexyl sebacate) (DOS), sodium tetrakis[3,5-bis(trifluoromethyl)phenyl]borate (NaTFPB), and silver ionophore IV ((O,O'-bis[2-methylthio]ethyl]-*tert*-butylcalix[4]arene) were obtained from Aldrich (Germany).



**Figure 2.** (A) Silver isotope ratio determined (from LA ICP–MS data) through the membrane thickness for a silver-selective membrane conditioned in (□) silver nitrate solution containing isotopically enriched silver (solution I) of concentration  $9.3 \times 10^{-4}$  M for 22 h or similarly pretreated membrane and then transferred to silver nitrate solution with natural isotope ratio of silver (solution N) of concentration  $10^{-3}$  M for different times (○) 1 h, (■) 2 h, (red ●) 22 h, (green ▼) 52 h, (blue ▲) 6 days; additionally, for comparison, isotope ratio for (▽) membrane conditioned for 22 h in silver nitrate solution of natural silver isotope abundance is shown. (B) Silver isotope ratio determined (from LA ICP–MS data) through the membrane thickness for a silver-selective membrane conditioned in (▽) silver nitrate solution of the natural ratio of silver isotopes N of concentration  $10^{-3}$  M for 22 h or similarly pretreated membrane and then transferred to the nitrate solution of isotopically enriched silver solution I of concentration  $9.3 \times 10^{-4}$  M for a different time: (■) 2 h, (red ●) 22 h, (blue ▲) 6 days; additionally, the isotope ratio for the (□) membrane conditioned for 22 h in silver nitrate solution of isotopically enriched silver (solution I) isotope abundance is shown.

Silver chloride was of analytical grade and was obtained from POCh (Gliwice, Poland). Ultrapure 65% nitric acid was from T. T. Baker (Phillipsburg, USA).

The isotopically enriched silver standard solution ( $^{109}\text{Ag}$  enriched) in 2% nitric acid with a certified concentration of  $(0.00091624 \pm 0.00001560)$  mol/kg from Innovative Solutions in Chemistry (ISC Science, Oviedo, Spain) was used.

The silver standard for ICP–MS measurements, TraceCERT, 1000 mg/L Ag in 2% nitric acid from Sigma-Aldrich (Steinheim, Germany) was used.

**Silver-Selective Membranes.** PVC-based membranes contained (in wt %) 2.2% of silver ionophore, 0.7% of NaTFPB, 65.5% of DOS, and 31.6% of PVC, and a total of 200 mg of membrane components were dissolved in 2 mL of THF. The typical, optimized content of the ion exchanger in the membrane applied also in this study is equal to 0.0079 mol/kg and ionophore 0.029 mol/kg.

Unless otherwise stated, 20  $\mu\text{L}$  (in 5  $\mu\text{L}$  portions) of the membrane cocktail solution was pipetted onto the polyacetate sheet and left for solvent evaporation under laboratory atmosphere for 2 h. Typical membranes of mass close to 1.5 mg and 150  $\mu\text{L}$  (being equivalent of 0.15 g) of the sample solution, for calculating actual mass of individual membrane, were used.

Unless otherwise stated, the thus obtained membranes on support were placed in individual Eppendorf vials filled with a solution containing 0.015 mg silver ions. Before the LA ICP–MS analysis, while changing the conditioning solution, the membranes were well rinsed with deionized water and dried with a tissue.

Unless otherwise stated, the membrane thickness was determined using a micrometer caliper and it was close to 200  $\mu\text{m}$ . The mass of each membrane was calculated from the difference between the mass of the polyacetate sheet and mass of the polyacetate sheet covered with a membrane.

**Apparatus.** An ICP mass spectrometer NexION300D (Perkin Elmer, Germany) equipped with the laser ablation system LSX-213 (Teledyne CETAC, USA) was used for LA ICP–MS measurements. The membranes were inserted in a cell on an X–Y–Z-translation stage. The exact position of the membrane was observed with a CCD camera as a viewing system under PC control. The applied laser energy was 3.2 mJ, the repetition rate was 5 Hz, and the spot size was 150  $\mu\text{m}$ .

An ICP mass spectrometer NexION300D (Perkin Elmer, Germany) equipped with a nebulizer (0.7 mL/min) and a cyclonic spray chamber (both from Glass Expansion, Australia) was applied for the measurement of isotope ratios in sample solutions. The instrument conditions were checked daily and adjusted for optimum sensitivity and repeatability of the isotope ratio measurements. The typical instrumental setup was a 0.8 L/min nebulizer gas flow; 9.0 V lens voltage; 1200 W ICP RF power; and 1700 W pulse stage voltage.

**ID ICP–MS Studies.** Thus, the experimental protocol applied for ISMs was typical for reverse ID ICP–MS studies. If not otherwise stated, the membranes were pretreated, that is, equilibrated, with a solution of isotopically enriched silver standard ( $\text{AgNO}_3$ ), as shown in Figure 1, containing 99.41% of  $^{109}\text{Ag}$  and 0.59% of  $^{107}\text{Ag}$ , (solution I). The preconditioning time was chosen to assure full saturation of the membrane, as determined before,<sup>22–25</sup> and this time was equal to 22 h. Then, the tested membranes were transferred to a silver nitrate solution of natural isotope ratio solution N of defined concentration for the chosen time to allow for ion exchange. The solutions N contained silver with a natural abundance of two isotopes: 48.16% of  $^{109}\text{Ag}$  and 51.84% of  $^{107}\text{Ag}$ .

## RESULTS AND DISCUSSION

The main aim of this work was to study primary ion exchange (here, silver ions) between the fully conditioned membrane and solution. For the systems in which the isotopic equilibrium was reached, we intend to determine directly the absolute concentration of silver ions present in the membrane. The application of analyte ions of different natural isotope ratios for studying ISM requires one easy acceptable assumption that the interactions with ISMs are the same for all isotopes of the ions of interest.

The exchange of silver ions between the membrane and solution (of initially different ratios of isotopes) leads to a change of the isotope ratio of silver in both phases, as shown in Figure 1. The isotopic equilibrium is dependent on time and concentration of the solution used, assuming that the concentration of  $\text{Ag}^+$  in replicates of nominally the same membranes, pretreated in the same way, is constant. To



maximize isotope ratio changes, isotopically enriched silver ion solution was used to pretreat the membrane. Then the membrane was transferred into a solution of the natural abundance of silver isotopes, the protocol used was similar to the one used in the reverse ID approach. Thus, the increase in  $^{107}\text{Ag}$  content in the membrane can be observed clearly by plotting a ratio of  $^{107}\text{Ag}/^{109}\text{Ag}$ .

To allow determination of the concentration of primary ions in the ISM, reaching isotopic equilibrium between the membrane preconditioned in isotopically enriched solution (I) and then transferring to a natural one (N) is necessary, as shown in Figure 1. This requires ion transfer through the interface and transport in the membrane bulk. The process is dependent both on concentration gradients and ion diffusion coefficients in the ISM and solution. Clearly, reaching equilibrium (constant isotope ratio within the ISM phase) requires longer time scales compared to liquid type samples, as the diffusion coefficients in ISMs are lower.<sup>22</sup> Ideally, the content of primary ions in the membrane phase is ruled by the concentration of ion exchanger in the membrane phase.

Using spatial resolution offered by laser ablation ICP-MS, we aim to estimate (i) the diffusion coefficient of silver ions in the membrane, based on the changes of isotope contents in time, ultimately in the equilibrium using ID ICP-MS for solutions and LA ID ICP-MS for membranes to determine (ii) the silver ion concentration in the membrane directly.

**Before the Isotopic Equilibrium State.** Figure 2A presents isotope ratios of  $^{107}\text{Ag}/^{109}\text{Ag}$  changes through the membrane thickness observed after the given membrane/solution contact times (to enable easier comparison of traces, the slopes of isotope ratio versus membrane thickness for given membrane-sample contact times are plotted in Figure S1). Because of the applied experimental procedure, preconditioning of the membrane in solution containing predominantly  $^{109}\text{Ag}$  (solution I) was applied to enhance the visibility of changes. Then, after conditioning in solution of the natural abundance of isotopes, the  $^{107}\text{Ag}/^{109}\text{Ag}$  ratio was plotted in all figures, to result in all traces of similar order of magnitude and ultimately, easier visualization of isotope ratio changes in the membrane phase.

Following pretreatment of ISM for 22 h, the  $^{109}\text{Ag}$  signal in the membrane was constant through the ISM phase thickness, confirming that the applied conditioning protocol leads to a primary ions-equilibrated membrane.<sup>22–25</sup>

Figure 2A shows that  $^{109}\text{Ag}$ -enriched solution pretreated membrane is, as expected, characterized by the constant isotope ratio in the membrane phase, close to 0, as there was low abundance of  $^{107}\text{Ag}$  in this solution. However, a significantly different dependence was obtained for a similarly pretreated membrane after following a 2 h contact with  $10^{-3}$  M  $\text{AgNO}_3$  solution of the natural abundance of both silver isotopes. The silver isotope ratio in the membrane changes through the thickness, from ca. 0.4 at the interface with solution to ca. 0.2 in the membrane bulk. This result clearly shows that ion exchange between the membrane and solution is in progress at 2 h contact time, and it is far from isotopic equilibrium.

After 22 h conditioning time in natural silver isotope ratio solution N, isotopic equilibrium in the membrane was still not reached, although isotope ratios were higher compared to the shorter contact time with the natural abundance of silver isotopes solution, as expected for progressing equilibration. The above results are, to the best of our knowledge, the first

experimental evidences showing the (long) ion exchange process occurring between primary ion-saturated ISM and solution. It seems important for the field to take into account that although these are surface sensors, the full equilibration with solution is a long-term process.

Based on the LA ICP-MS measurements, concerning conditioning in  $^{109}\text{Ag}$ -enriched solution and then contact with solution N (Figure 2A), the rate of transport of silver ions in the membrane can be also studied. Assuming that the ion transport is governed by diffusion, the following equation can be used<sup>45</sup>

$$-\ln(1 - F) = \frac{\pi^2 Dt}{4\Delta^2} + \text{const} \quad (1)$$

where  $D$  is the diffusion coefficient in the membrane,  $\Delta$  is the distance covered in the membrane,  $t$  is time, while  $F$  is the exchange ratio.

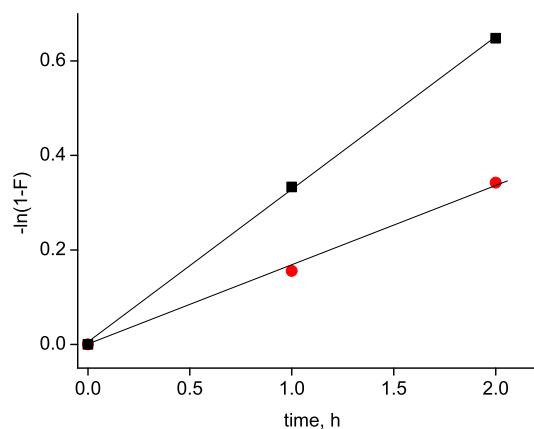
$$F = \frac{x - x_0}{x_\infty - x_0} \quad (2)$$

where  $x$  is the mole ratio of  $^{107}\text{Ag}$  related to total amount of silver, and subscripts 0 and  $\infty$  (as previously<sup>22</sup>) relate to initial and equilibrium state, respectively.

The mole ratio of the  $^{107}\text{Ag}$  isotope,  $x$ , can be calculated from the signal intensity ratio of  $^{107}\text{Ag}/^{109}\text{Ag}$ , as shown in Figure 2, and this ratio is described as  $R$

$$x = R/(R + 1) \quad (3)$$

Plots of  $-\ln(1 - F)$  versus  $t$  for two distances from the membrane/solution interface are presented in Figure 3. A



**Figure 3.** Dependence of  $-\ln(1 - F)$  on time (eq 1) for the distance in the membrane phase: (■)  $\Delta = 120 \mu\text{m}$  or (red ●)  $\Delta = 200 \mu\text{m}$ .

linear dependence is observed as expected from eq 1. From the slopes of the dependences, the diffusion coefficient can be calculated, and the results obtained from both plots are similar within the limits of experimental error and equal to  $(6 \pm 1) \times 10^{-9} \text{ cm}^2/\text{s}$ . The error of determination is smaller than what was obtained by using previously described methods. This is directly related to the methodology applied here, that is, looking for a linear relation between the exchange ratio and time, contrary to intensity versus distance dependence, as shown in Figure S2, especially taking into account the exponential decay of the intensity signal on thickness in the latter case. The main source of error in the diffusion coefficient determination in this work is the uncertainty in membrane

thickness,  $\Delta$  (eq 1) value. The estimated diffusion coefficient is a few times smaller than the analogous value for  $K^+$ -valinomycin complex in a plasticized PVC membrane,<sup>22</sup> obtained for membranes in course of saturation with primary ions.

It should be stressed that using a previously described approach<sup>22</sup> for 270  $\mu\text{m}$  thick membranes as prepared and then pretreating for 155 min in  $10^{-3}$  M  $\text{AgNO}_3$  (solution N), as shown in Figure S2, resulted in similar silver ion diffusion coefficients equal to  $(7 \pm 3) \times 10^{-9}$   $\text{cm}^2/\text{s}$ , that is, within the range of the experimental error comparable to the diffusion coefficient obtained for the already pretreated membrane.

The rate of equilibration of ISMs with the solution can be affected by different factors. The main possible limiting factors are (i) slow diffusion of ions within the membrane and (ii) slow dissociation of a very stable complex  $\text{Ag}^+$ -ionophore. Assuming that ionophore–primary ion complex dissociation is a first-order kinetic process, the rate of equilibration process should be independent of the membrane thickness. Therefore, the effect of membrane thickness on the time needed to reach isotopic equilibrium was studied. Contrary to the above-described membranes (200  $\mu\text{m}$  thick), for thinner membranes, 100  $\mu\text{m}$ , isotopic equilibrium in the ISM was reached within 22 h time (results not shown). This influence of the membrane thickness clearly suggests that the complex dissociation process is not the rate-limiting step in isotopic equilibration, but transport in the membrane.

Taking into account the above given silver ion diffusion coefficient in the preconditioned membrane and membrane thickness (200  $\mu\text{m}$ ), the time needed for silver ions to cross the membrane thickness [assuming simplified approach  $D = L^2/t$ , where  $D$  is the diffusion coefficient ( $6 \times 10^{-9}$   $\text{cm}^2/\text{s}$ ),  $L$  is the membrane thickness (cm), and  $t$  is time (s)] can be estimated to be close to 18 h, close to the experimentally determined time required to saturate the membrane with primary ions. This time is expected to be the minimum time required to reach isotopic equilibrium between the membrane and solution, which is an analogue of equilibration of the membrane with a sample of the same concentration (new portion of the solution).

The herein reported information on ion diffusion through the membrane already containing primary ions being a rate-limiting step in ion exchange between ISMs and solution, considering ion transfer through the interface as a fast process,<sup>44</sup> is in good agreement with the previous reports showing high silver loadings of the membrane region close to the solution interface.<sup>29</sup>

**Isotopic Equilibrium State.** The experiment concerning the isotopic equilibrium state was performed after 52 h of membrane contact with solution N  $10^{-3}$  M solution (after membranes were pretreated for 22 h in solution I). As expected, it was observed that isotopic equilibrium was reached in the whole system: through the thickness of the membrane and between the membrane and solution. The isotope ratio  $^{107}\text{Ag}/^{109}\text{Ag}$  ( $\pm\text{SD}$ ) was equal to  $0.9418 \pm 0.0404$  and  $0.9645 \pm 0.0116$  for the membrane and solution, respectively (equivalent to  $^{109}\text{Ag}/^{107}\text{Ag}$   $1.064 \pm 0.046$  and  $1.038 \pm 0.012$ , for membrane and solution, respectively). Accordingly, isotopic equilibrium was observed in the next experiment performed after 6 days of membrane contact with solution N, and the isotope ratio  $^{107}\text{Ag}/^{109}\text{Ag}$  in the membrane was constant through its thickness and equal to  $0.8925 \pm 0.0408$ , which corresponds to the  $^{109}\text{Ag}/^{107}\text{Ag}$  ratio of  $1.126 \pm 0.062$ .

For the same conditioning time, the isotope  $^{109}\text{Ag}/^{107}\text{Ag}$  ratio in solution was equal to  $1.126 \pm 0.032$ .

For the isotopic equilibrium prevailing in the system (in the membrane and between the membrane and solution) both for 52 h and 6 days contact time, using a set of equations describing the mathematical model of ID approach, Table S1, Supporting Information, allows for calculation of the silver concentration in the membrane, as shown in Table 1.

**Table 1. Silver Concentration Assumed to Silver Ions in Tested Membranes as a Function of Contacting Solution Concentration, Tested Systems were Pretreated in the Isotopically Enriched Solution I of  $\text{AgNO}_3$  of  $9.3 \times 10^{-4}$  M for 22 h and Then were Transferred for 6 Days to the Solution of the Natural Abundance of Silver Isotopes, N, of Different Concentrations; Alternatively They were Pretreated in Solution N of  $10^{-3}$  M for 22 h and were Transferred for 6 Days to the Solution of Isotopically Enriched Solution I of  $\text{AgNO}_3$  of Different Concentrations<sup>a</sup>**

pretreatment solution	52 h contact with the solution	the concentration of silver in the membrane $\pm U$ ( $k = 2$ ), mol/kg
I, $9.3 \times 10^{-4}$ M	N, $10^{-3}$ M	$0.012 \pm 0.002$
	6 Days Contact with the Solution	
I, $9.3 \times 10^{-4}$ M	N, $10^{-3}$ M	$0.012 \pm 0.002$
I, $9.3 \times 10^{-4}$ M	N, $10^{-2}$ M	$0.015 \pm 0.002$
I, $9.3 \times 10^{-4}$ M	N, $10^{-4}$ M	$0.012 \pm 0.001$
N, $10^{-3}$ M	I, $10^{-3}$ M	$0.011 \pm 0.002$
N, $10^{-3}$ M	I, $10^{-4}$ M	$0.011 \pm 0.001$
N, $10^{-3}$ M	I, $10^{-5}$ M	$0.011 \pm 0.002$

<sup>a</sup>In all cases, the ion-exchanger concentration in the membrane was equal to 0.0079 mol/kg. Reported uncertainties represent expanded uncertainties ( $U$ ) expressed at approximately the 95% confidence level using a coverage factor ( $k$ ) of  $k = 2$  namely:  $U$ —expanded uncertainty,  $k$ —coverage factor,  $k = 2$  represents approximately a 95% confidence level.

From the results shown in Table 1, it is clear that both 52 h or 6 days contact of the silver-selective membrane with  $10^{-3}$  M solution results in similar, within the range of experimental uncertainty, contents of silver in the membrane close to  $0.012 \pm 0.002$  mol/kg ( $\pm U$ ,  $k = 2$ ). The obtained value is significantly higher compared to the amount of ion exchanger introduced to the membrane, that is, 0.0079 mol/kg. Thus, contrary to the previous report,<sup>30</sup> it is clearly shown that conditioning of the silver-selective membrane in  $10^{-3}$  M solution of primary ions leads to accumulation in the membrane of a higher amount of silver compared to the amount of ion exchanger used of about 50%.

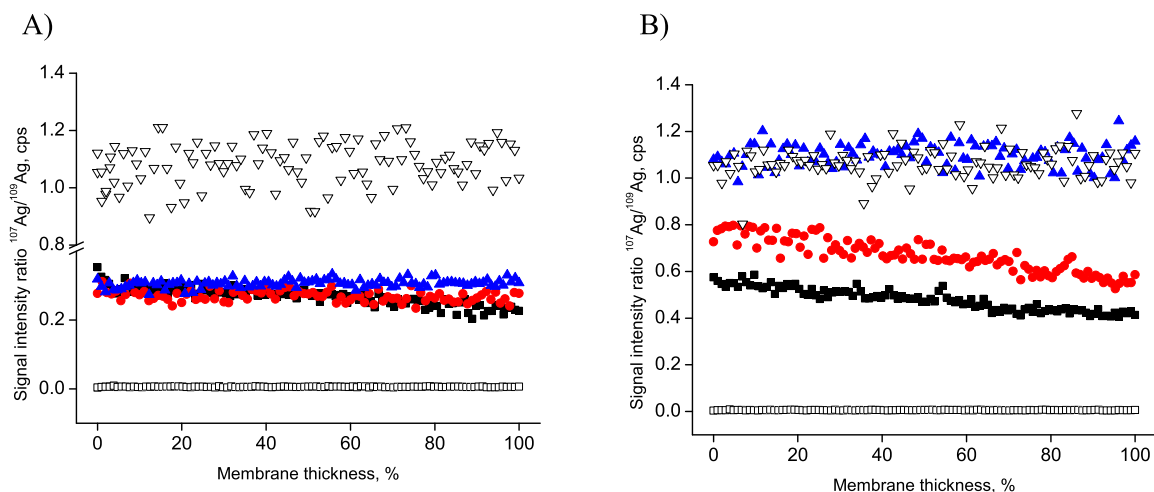
For the system herein studied also an approach based on a simple mass balance can be used. Under these isotopic equilibrium conditions, for the isotope  $^{107}\text{Ag}$  one can write

$$cV(x_{0,s} - x_{\infty,s}) = C_{\text{Ag}}M(x_{\infty,m} - x_{0,m}) \quad (4)$$

$$x_{\infty,m} = x_{\infty,s} \quad (5)$$

where  $c$  is the molar concentration of silver ions in a solution of volume  $V$ ,  $C_{\text{Ag}}$  is the molal (mol/kg) concentration of silver ions in the membrane of mass,  $M$ ,  $x_0$ , and  $x_\infty$  are initial and equilibrium mole ratios of the  $^{107}\text{Ag}$  isotope (in relation to total amount of silver), respectively, in the solution (s) or the membrane (m).

Using known values,  $c$ ,  $V$ ,  $M$ , and mole ratios, one can estimate the  $C_{\text{Ag}}$ .



**Figure 4.** (A) Isotope ratio determined (from LA ICP–MS data) through the membrane thickness for silver-selective membrane conditioned in (□) silver nitrate solution of isotopically enriched silver (solution I) of concentration  $9.3 \times 10^{-4}$  M for 22 h or similarly pretreated membrane and then transferred to silver nitrate solution of natural silver isotope abundance (solution N) of concentration  $10^{-4}$  M for different times (■) 2 h, (red ●) 22 h, (blue ▲) 6 days; additionally, the isotope ratio for the (▽) membrane conditioned for 22 h in silver nitrate solution of natural silver isotope abundance is shown. (B) Isotope ratio determined (from LA ICP–MS data) through the membrane thickness for silver selective membrane conditioned in (□) silver nitrate solution of isotopically enriched silver (solution I) of concentration  $9.3 \times 10^{-4}$  M for 22 h or similarly pretreated membrane and then transferred to silver nitrate solution of natural silver isotope abundance (solution N) of concentration  $10^{-2}$  M for different times (■) 2 h, (red ●) 22 h, (blue ▲) 6 days; additionally, the isotope ratio for (▽) membrane conditioned for 22 h in silver nitrate solution of natural silver isotope abundance is shown.

Analogous calculations can be carried out for the isotope  $^{109}\text{Ag}$ , where

$$cV(x_{\infty,s} - x_{0,s}) = C_{\text{Ag}}M(x_{0,m} - x_{\infty,m}) \quad (6)$$

Using this equation with eq 4, the value  $C_{\text{Ag}}$  can be again estimated. The  $C_{\text{Ag}}$  values obtained in both cases are within the limits of experimental error, the same.

Based on eqs 4–6, the calculated silver ions concentration in the membrane after 6 days conditioning was  $0.010 \pm 0.001$  mol/kg. It is close, within the range of experimental error, to the value shown in Table 1, obtained using equations given in Table S1.

Complementary results obtained for a membrane initially preconditioned in the solution of natural abundance of silver isotopes,  $10^{-3}$  M solution N, are shown in Figure 2B. For this system following transfer to the isotopically enriched solution (solution I) for 2 h, similar to that presented in Figure 2A, the isotope ratio was affected primarily close to the membrane/solution interface. Deeper in the bulk of ISM, not much change was observed. After 22 h contact of the membrane with the solution I, more pronounced changes in isotope ratio have occurred, yet the isotope ratio in the membrane was not constant, similar to the case shown in Figure 2A. After 6 days of the membrane bathing in the isotopically enriched silver solution I, the isotope ratio of  $^{107}\text{Ag}/^{109}\text{Ag}$  in the ISM was constant and equal to  $0.0441 \pm 0.0033$ . In the solution in which the membrane was conditioned, the isotope ratio of  $^{107}\text{Ag}/^{109}\text{Ag}$  after 6 days was equal to  $0.0461 \pm 0.0011$ . These results clearly show that both within the ISM and between the membrane and the solution, the isotopic equilibrium was reached within 6 days and they support the observation from reverse ID mode. The silver concentration in the membrane calculated from these values was equal to  $0.011 \pm 0.001$  mol/kg. The obtained result is within the range of uncertainty equal to that calculated for the system pretreated in solution I and then transferred to solution, N; thus it clearly supports the

assumption of indifference of the isotopes with respect to interactions with ISMs.

It should be stressed that for membrane preconditioned in the solution I of concentration close to  $10^{-3}$  M and then transferred to solution N, or vice versa, the isotope ratio obtained after 6 days of conditioning was significantly different from that characterizing either solution I or N. This result is, however, expected, taking into account different total amounts of silver ions present in the membrane, close to the mole amount of ion exchanger used, for example, to  $1.18 \times 10^{-8}$  mol (corresponding to concentration in the membrane close to above  $1 \times 10^{-3}$  M), moreover taking into account that the increased silver amount in the membrane is ca. 50% compared to the amount of ion exchanger used, it is close to  $1.8 \times 10^{-8}$  mol and in the  $150 \mu\text{L}$  of the solution of concentration close to/equal to  $10^{-3}$  M, being  $1.5 \times 10^{-7}$  mol, that is, 1 order of magnitude different.

However, pretreating of the membrane in  $10^{-3}$  M solution N and transferring it to the solution I of concentration of  $10^{-5}$  M, after 6 days of membrane–solution contact time due to more favorable amounts of silver isotopes resulted in reaching isotopic equilibrium in the system. Ratios of isotopes were equal to  $^{107}\text{Ag}/^{109}\text{Ag}$  0.9167  $\pm$  0.0397 in the membrane and  $0.9063 \pm 0.0091$  in solution (however, only slightly lower than natural one), allowing for calculation of the membrane concentration of silver, as shown in Table 1. The obtained silver concentration was equal to  $0.011 \pm 0.001$  mol/kg, and it was well comparable, with the uncertainty, to the value obtained for membranes that were in contact with the more concentrated sample solution.

The above presented results were compared with the data for another system now, for which after preconditioning in the solution I of concentration close to  $10^{-3}$  M, the membrane was transferred to  $10^{-4}$  M silver ion solution N, as shown in Figure 4A. In this case, the availability of silver ions in the solution N is lower compared to a more concentrated solution I, and thus



the isotope ratio value is not much affected by conditioning time. Similar as in the previous case, to achieve isotope ratio values that are constant through the membrane phase, 22 h conditioning time was not sufficient. After 6 days of conditioning, the isotope ratio of  $^{107}\text{Ag}/^{109}\text{Ag}$  in the membrane was constant through its thickness and equal to  $0.3057 \pm 0.0123$ , which corresponds to the  $^{109}\text{Ag}/^{107}\text{Ag}$  ratio of  $3.276 \pm 0.136$ . For the same conditioning time, the  $^{109}\text{Ag}/^{107}\text{Ag}$  isotope ratio in solution was equal to  $3.218 \pm 0.121$ . From the point of view of ID, this concentration match is preferred, as it leads to significant alteration of the natural isotope ratio. The calculated value of silver ions concentration in the membrane was equal to  $0.012 \pm 0.001$  mol/kg, as shown in Table 1, which is in good agreement with that obtained for other tested systems, as shown in Table 1.

The process leading to excess (with respect to the ion exchanger) silver present in the membrane can involve coextraction driven by high ionophore–analyte binding constant and the presence of relatively lipophilic nitrate anions in the sample. The chemical form of excess silver present in the membrane is also obscured for the methodology applied in this study. The intuitive explanation can be the presence of electrolyte droplets within the membrane phase, which is in line with previously reported effect of contact with a diluted solution on the potentiometric performance.<sup>26</sup> However, the above presented results clearly show that contact of membranes previously equilibrated in  $10^{-3}$  M  $\text{AgNO}_3$  with a diluted solution (e.g.  $10^{-5}$  M  $\text{AgNO}_3$ ) results in relatively small decrease of excess silver present in the membrane, suggesting that there are also other processes involved that result in an overall strong “memory effect” of the membrane.

It should be stressed that the above given concentrations of primary ions in the membrane are (as expected) affecting the recorded potentiometric dependencies, as shown in Figure S3. For membranes pretreated at  $\text{AgNO}_3$  of concentration  $10^{-4}$  and  $10^{-5}$  M, as expected,<sup>26,29,30</sup> the difference prevails at lower concentrations. However, as membranes of these sensors have not been equilibrated with  $10^{-3}$  M solution as the system studied by ID approach, the comparison between potentiometric responses and silver contents in the membrane cannot be made in these cases. For membranes conditioned in  $10^{-3}$  M  $\text{AgNO}_3$ , that is, for the system for which ID approach resulted in a certain amount of silver being present in the membrane close to 150% of the amount of ion exchanger, a linear dependence of potential on logarithm of silver ion activity was obtained within the concentration range from  $10^{-2}$  to  $10^{-5}$  M with a slope equal to  $53.0 \pm 1.4$  mV/dec ( $R^2 = 0.998$ ) and detection limit equal to  $10^{-5.2}$  M, as shown in Figure S3. The deviation from the Nernstian slope was observed only for a concentration change from  $10^{-2}$  to  $10^{-1}$  M, for which the potential change was equal to 43.2 mV. The obtained result is quite surprising, taking into account the high excess silver ions present in the membrane found in ID studies, as shown in Table 1.

Potentiometric performance of membranes pretreated in  $10^{-2}$  M  $\text{AgNO}_3$  can be compared with results of ID silver content determination for the systems that after pretreatment were in contact with  $10^{-2}$  M solution, assuming that membrane memory effects are minor in this case. For this system, a linear dependence of potential on the logarithm of silver ion activity was obtained within the concentration range of  $10^{-2}$  to  $10^{-4}$  M with a slope equal to  $54.8 \pm 0.8$  mV/dec ( $R^2 = 0.998$ ) and detection limit equal to  $10^{-4.9}$  M, Figure S3. As

expected, the contact of the membrane with more concentrated silver ions solution resulted in a higher detection limit. The more pronounced deviation from the Nernstian slope was observed also for the concentration change from  $10^{-2}$  to  $10^{-1}$  M, for which the potential change was equal to 38.5 mV. Thus, clearly, higher content of silver in the solution leads to a more pronounced deviation from Nernstian performance of the sensor. Thus, potentiometric results obtained are in line with results of the ID silver presence in the membrane quantification; moreover, these are raising the questions about the nature of excess found. Clearly, more studies on the phenomena observed are required, as the nature of excess (with respect to the ion exchanger) silver present in the membrane is obscured to the methodology used in this study.

Figure 4B presents results of the experiment, in which  $10^{-2}$  M solution N was used after membrane pretreatment in solution I ( $9.3 \times 10^{-4}$  M). In this experiment, solution N was a source of silver ions, nevertheless, both after 2 and 22 h of membrane contact with sample solution, the isotope ratio within the membrane changed through its thickness. However, this is expected, taking into account that the rate-limiting step in equilibration is silver ion diffusion in the preconditioned membrane, not the availability of ions in the sample solution. After 6 days of conditioning, the constant value of the isotope ratio in the membrane prevailed, and the obtained value of the isotope ratio of  $^{107}\text{Ag}/^{109}\text{Ag}$  was equal to  $1.043 \pm 0.053$ , which corresponds to the  $^{109}\text{Ag}/^{107}\text{Ag}$  ratio of  $0.9591 \pm 0.0462$ . It should be underlined that this value well corresponds to the value obtained for the membrane conditioned in  $10^{-3}$  M solution N, that is, solution of the natural abundance of silver isotopes. Again, the obtained result is expected, taking into account the ratio of spike, that is, amount of isotopically enriched silver accumulated in the membrane after pretreatment and a significantly higher amount of silver present in the standard. The isotope ratio in the solution was equal to  $0.9592 \pm 0.0463$ . Clearly, the isotopic equilibrium was reached in the system; however, as the ratio of isotopes is not far from the natural one, the result of calculation,  $0.015 \pm 0.002$  mol/kg, from a metrological point of view needs to be treated as the estimated concentration only, as shown in Table 1.

## CONCLUSIONS

In this work, for the first time, the exchange of ions between a fully pretreated ISM and solution containing its primary ions was experimentally shown. As the model system, silver-selective membranes were studied. To observe the ion exchange occurring, the solutions used were either of the natural abundance of silver isotopes or isotopically enriched one, and distribution of natural isotopes with spatial resolution LA ICP–MS was used. The ID approach used allowed us, for the first time, to observe and quantify directly the silver ion diffusion process in the pretreated membrane, that is, in the membrane already containing silver ions. The obtained diffusion coefficient was equal to  $6 \times 10^{-9}$  cm<sup>2</sup>/s, comparable with that characterizing incorporation of silver ions to the as-prepared silver ion-free membrane. Slow diffusion of silver ions in the membrane was the rate-limiting step in reaching isotopic equilibrium in the system. For the system with prevailing equilibrium, the ID approach was used to quantify silver contents in the membrane. It was found that contact of the ISMs with  $10^{-3}$  M or lower concentration of  $\text{AgNO}_3$  solution results in silver contents of around 50% higher than that of ion exchanger used. This effect was more pronounced for higher

concentrations of AgNO<sub>3</sub>. Although the obtained results do not give insights into the nature of process occurring, they clearly suggest that the amount of primary ions present in the membrane can be higher than assumed, taking into account the amount of ion exchanger used, especially in the presence of relatively lipophilic anions in the sample.

## ■ ASSOCIATED CONTENT

### SI Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acssensors.0c01585>.

ID: Comparison of slopes of isotope ratio plotted versus membrane thickness for different membrane–sample for different contact times, intensity changes of the <sup>107</sup>Ag signal as a function of laser ablation ICP-MS penetration depth obtained for tested membranes, potentiometric dependencies recorded for ion-selective electrodes pretreated in different concentrations of AgNO<sub>3</sub>, and equations used for quantification of silver content according to the IDMS theory (PDF)

## ■ AUTHOR INFORMATION

### Corresponding Authors

Krzysztof Maksymiuk – Faculty of Chemistry, University of Warsaw, 02-093 Warsaw, Poland; [orcid.org/0000-0002-3931-3798](https://orcid.org/0000-0002-3931-3798); Email: [kmaks@chem.uw.edu.pl](mailto:kmaks@chem.uw.edu.pl)

Agata Michalska – Faculty of Chemistry, University of Warsaw, 02-093 Warsaw, Poland; [orcid.org/0000-0002-8509-1428](https://orcid.org/0000-0002-8509-1428); Email: [agatam@chem.uw.edu.pl](mailto:agatam@chem.uw.edu.pl)

### Authors

Agnieszka Anna Krata – Faculty of Chemistry, University of Warsaw, 02-093 Warsaw, Poland; Biological and Chemical Research Centre, University of Warsaw, 02-089 Warsaw, Poland

Emilia Stelmach – Faculty of Chemistry, University of Warsaw, 02-093 Warsaw, Poland

Marcin Wojciechowski – Faculty of Chemistry, University of Warsaw, 02-093 Warsaw, Poland; Biological and Chemical Research Centre, University of Warsaw, 02-089 Warsaw, Poland

Ewa Bulska – Faculty of Chemistry, University of Warsaw, 02-093 Warsaw, Poland; Biological and Chemical Research Centre, University of Warsaw, 02-089 Warsaw, Poland

Complete contact information is available at:

<https://pubs.acs.org/doi/10.1021/acssensors.0c01585>

### Notes

The authors declare no competing financial interest.

## ■ ACKNOWLEDGMENTS

The experimental work was performed within the years 2017–2019. Financial support from National Science Centre (NCN, Poland) is gratefully acknowledged: for years 2014–2017 from project 2013/09/B/ST4/00949 and for years 2019–2022 from project 2018/31/B/ST4/02699.

## ■ REFERENCES

(1) Nahir, T. M.; Buck, R. P. Transport Properties of H<sup>+</sup>-Selective Membranes Containing Amine-Derivative Ionophores and Mobile Sites. *Helv. Chim. Acta* **1993**, *76*, 407–415.

(2) Gyurcsányi, R. E.; Pergel, É.; Nagy, R.; Kapui, I.; Thu Lan, B. T.; Tóth, K.; Bitter, L.; Lindner, E. Direct Evidence of Ionic Fluxes Across Ion-Selective Membranes: A Scanning Electrochemical Microscopic and Potentiometric Study. *Anal. Chem.* **2001**, *73*, 2104–2111.

(3) Horvai, G.; Gráf, E.; Tóth, K.; Pungor, E.; Buck, R. P. Plasticized Poly(Vinyl Chloride) Properties and Characteristics of Valinomycin Electrodes. 1. High-Frequency Resistances and Dielectric Properties. *Anal. Chem.* **1986**, *58*, 2735–2740.

(4) Tóth, K.; Gráf, E.; Horvai, G.; Pungor, E.; Buck, R. P. Plasticized Poly(Vinyl Chloride) Properties and Characteristics of Valinomycin Electrodes. 2. Low-Frequency, Surface-Rate, and Warburg Impedance Characteristics. *Anal. Chem.* **1986**, *58*, 2741–2744.

(5) Kellner, R.; Fischböck, G.; Götzinger, G.; Pungor, E.; Tóth, K.; Pólos, L.; Lindner, E. FTIR-ATR Spectroscopic Analysis of bis-Crown-Ether Based PVC-Membrane Surfaces. *Fresenius. J. Anal. Chem.* **1985**, *322*, 151–156.

(6) Tohda, K.; Umezawa, Y.; Yoshiyagawa, S.; Hashimoto, S.; Kawasaki, M. Cation Permselectivity at the Phase Boundary of Ionophore-Incorporated Solvent Polymeric Membranes as Studied by Optical Second Harmonic Generation. *Anal. Chem.* **1995**, *67*, 570–577.

(7) Jaber, A. M. Y.; Moody, G. J.; Thomas, J. D. R.; Willcox, A. Radiotracer studies on ion-selective membranes based on poly(vinyl chloride) matrices. *Talanta* **1977**, *24*, 655–657.

(8) Doyle, B.; Moody, G. J.; Thomas, J. D. R. Radiotracer studies on ion-selective electrode membranes containing metal complexes of a nonylphenoxypoly(ethyleneoxy)ethanol in poly(vinyl chloride) matrices. *Talanta* **1982**, *29*, 257–262.

(9) Thoma, A. P.; Vivlanl-Nauer, A.; Arvanitis, S.; Morf, W. E.; Simon, W. Mechanism of Neutral Carrier Mediated Ion Transport through Ion-Selective Bulk Membranes. *Anal. Chem.* **1977**, *49*, 1567–1572.

(10) Schneider, B.; Zwickl, T.; Federer, B.; Pretsch, E.; Lindner, E. Spectropotentiometry: A New Method for in Situ Imaging of Concentration Profiles in Ion-Selective Membranes with Simultaneous Recording of Potential–Time Transients. *Anal. Chem.* **1996**, *68*, 4342–4350.

(11) Lindner, E.; Zwickl, T.; Bakker, E.; Lan, B. T. T.; Tóth, K.; Pretsch, E. Spectroscopic in Situ Imaging of Acid Coextraction Processes in Solvent Polymeric Ion-Selective Electrode and Optode Membranes. *Anal. Chem.* **1998**, *70*, 1176–1181.

(12) Gyurcsányi, R. E.; Lindner, E. Spectroscopic Method for the Determination of the Ionic Site Concentration in Solvent Polymeric Membranes and Membrane Plasticizers. *Anal. Chem.* **2002**, *74*, 4060–4068.

(13) Gyurcsányi, R. E.; Lindner, E. Spectroelectrochemical Microscopy: Spatially Resolved Spectroelectrochemistry of Carrier-Based Ion-Selective Membranes. *Anal. Chem.* **2005**, *77*, 2132–2139.

(14) Heng, L.; Tóth, K.; Hall, E. A. H. Ion-Transport and Diffusion Coefficients of Non-Plasticized Methacrylic-Acrylic Ion-Selective Membranes. *Talanta* **2004**, *63*, 73–87.

(15) Long, R.; Bakker, E. Optical Determination of Ionophore Diffusion Coefficients in Plasticized Poly(Vinyl Chloride) Sensing Films. *Anal. Chim. Acta* **2004**, *511*, 91–95.

(16) Veder, J.-P.; De Marco, R.; Clarke, G.; Chester, R.; Nelson, A.; Prince, K.; Pretsch, E.; Bakker, E. Elimination of Undesirable Water Layers in Solid-Contact Polymeric Ion-Selective Electrodes. *Anal. Chem.* **2008**, *80*, 6731–6740.

(17) Veder, J.-P.; Patel, K.; Clarke, G.; Grygolowicz-Pawlak, E.; Silvester, D. S.; De Marco, R.; Pretsch, E.; Bakker, E. Synchrotron Radiation/Fourier Transform-Infrared Microspectroscopy Study of Undesirable Water Inclusions in Solid-Contact Polymeric Ion-Selective Electrodes. *Anal. Chem.* **2010**, *82*, 6203–6207.

(18) Wang, Z.; Kotobuki, M.; Lu, L.; Zeng, K. Nanoscale Characterization of Solid Electrolyte by Scanning Probe Microscopy Techniques. *Electrochim. Acta* **2019**, *334*, 135553.

(19) Bodor, S.; Zook, J. M.; Lindner, E.; Tóth, K.; Gyurcsányi, R. E. Chronopotentiometric Method for the Assessment of Ionophore



Diffusion Coefficients in Solvent Polymeric Membranes. *J. Solid State Electrochem.* **2009**, *13*, 171–179.

(20) Zook, J. M.; Bodor, S.; Lindner, E.; Tóth, K.; Gyurcsányi, R. E. Assessment of Ion-Ionophore Complex Diffusion Coefficients in Solvent Polymeric Membranes. *Electroanalysis* **2009**, *21*, 1923–1930.

(21) Oesch, U.; Simon, W. Kinetische Betrachtung der Verteilung von elektrisch neutralen Ionophoren zwischen einer Flüssigmembran und einer wässrigen Phase. *Helv. Chim. Acta* **1979**, *62*, 754–767.

(22) Michalska, A.; Wojciechowski, M.; Wagner, B.; Bulska, E.; Maksymiuk, K. Laser Ablation Inductively Coupled Plasma Mass Spectrometry Assisted Insight into Ion-Selective Membranes. *Anal. Chem.* **2006**, *78*, 5584–5589.

(23) Rzewuska, A.; Wojciechowski, M.; Bulska, E.; Hall, E. A. H.; Maksymiuk, K.; Michalska, A. Composite Polyacrylate-Poly(3,4-ethylenedioxythiophene) Membranes for Improved All-Solid-State Ion-Selective Sensors. *Anal. Chem.* **2008**, *80*, 321–327.

(24) Jaworska, E.; Kisiel, A.; Maksymiuk, K.; Michalska, A. Lowering the Resistivity of Polyacrylate Ion-Selective Membranes by Platinum Nanoparticles Addition. *Anal. Chem.* **2011**, *83*, 438–445.

(25) Woźnica, E.; Wójcik, M. M.; Wojciechowski, M.; Mieczkowski, J.; Bulska, E.; Maksymiuk, K.; Michalska, A. Dithizone Modified Gold Nanoparticles Films for Potentiometric Sensing. *Anal. Chem.* **2012**, *84*, 4437–4442.

(26) Woźnica, E.; Wójcik, M. M.; Wojciechowski, M.; Mieczkowski, J.; Bulska, E.; Maksymiuk, K.; Michalska, A. Improving the Upper Detection Limit of Potentiometric Sensors. *Electroanalysis* **2015**, *27*, 720–726.

(27) Jaworska, E.; Naitana, M. L.; Stelmach, E.; Pomarico, G.; Wojciechowski, M.; Bulska, E.; Maksymiuk, K.; Paolesse, R.; Michalska, A. Introducing Cobalt(II) Porphyrin/Cobalt(III) Corrole Containing Transducers for Improved Potential Reproducibility and Performance of All-Solid-State Ion-Selective Electrodes. *Anal. Chem.* **2017**, *89*, 7107–7114.

(28) Kisiel, A.; Woźnica, E.; Wojciechowski, M.; Bulska, E.; Maksymiuk, K.; Michalska, A. Potentiometric Layered Membranes. *Sens. Actuators, B* **2015**, *207*, 995–1003.

(29) Skórska, L.; Michalska, A.; Wojciechowski, M.; Bulska, E.; Maksymiuk, K. Estimation of Primary Silver Ions Contents in Poly(Vinyl Chloride) Ion-Selective Membranes Using Chronopotentiometry and Mass Spectrometry. *Electrochim. Acta* **2012**, *73*, 86–92.

(30) Michalska, A.; Wojciechowski, M.; Bulska, E.; Maksymiuk, K. Quantifying Primary Silver Ions Contents in Poly(vinyl chloride) and Poly(n-butyl acrylate) Ion-Selective Membranes. *Electroanalysis* **2009**, *21*, 1931–1938.

(31) De Bièvre, P. SAC 92. Isotope Dilution Mass Spectrometry as a Primary Method of Analysis. *Anal. Proc.* **1993**, *30*, 328–333.

(32) Krata, A. A.; Wojciechowski, M.; Vassileva, E.; Bulska, E. Reference Measurements of Mercury Species in Seafood Using Isotope Dilution Inductively Coupled Plasma Mass Spectrometry. *J. Food Compos. Anal.* **2020**, *86*, 103381.

(33) Rahman, G. M. M.; Wolle, M. M.; Fahrenholz, T.; Kingston, H. M. S.; Pamuku, M. Measurement of Mercury Species in Whole Blood Using Speciated Isotope Dilution Methodology Integrated with Microwave-Enhanced Solubilization and Spike Equilibration, Head-space–Solid-Phase Microextraction, and GC-ICP-MS Analysis. *Anal. Chem.* **2014**, *86*, 6130–6137.

(34) Clough, R.; Belt, S. T.; Evans, E. H.; Fairman, B.; Catterick, T. Investigation of Equilibration and Uncertainty Contributions for the Determination of Inorganic Mercury and Methylmercury by Isotope Dilution Inductively Coupled Plasma Mass Spectrometry. *Anal. Chim. Acta* **2003**, *500*, 155–170.

(35) Vassileva, E.; Wysocka, I.; Betti, M. Reference Measurements for Cadmium, Copper, Hg, Lead, Zinc and Methyl Hg Mass Fractions in Scallop Sample by Isotope Dilution Inductively Coupled Plasma Mass Spectrometry. *Microchem. J.* **2014**, *116*, 197–205.

(36) Bulska, E.; Krata, A.; Kalabun, M.; Wojciechowski, M. On the Use of Certified Reference Materials for Assuring the Quality of Results for the Determination of Hg in Environmental Samples. *Environ. Sci. Pollut. Res.* **2017**, *24*, 7889–7897.

(37) Alonso, J.; Gonzalez, P. *Isotope Dilution Mass Spectrometry*, 1st edn.; Royal Society of Chemistry, May 30, 2013.

(38) Monperrus, M.; Rodriguez Martin-Doimeadios, R. C.; Scancar, J.; Amouroux, D.; Donard, O. F. X. Simultaneous Sample Preparation and Species-Specific Isotope Dilution Mass Spectrometry Analysis of Monomethylmercury and Tributyltin in a Certified Oyster Tissue. *Anal. Chem.* **2003**, *75*, 4095–4102.

(39) Qvarnström, J.; Lambertsson, L.; Havarinasab, S.; Hultman, P.; Frech, W. Determination of Methylmercury, Ethylmercury and Inorganic Mercury in Mouse Tissues, Following Administration of Thimerosal, by Species-Specific Isotope Dilution GC-Inductively Coupled Plasma MS. *Anal. Chem.* **2003**, *75*, 4120–4124.

(40) Queipo Abad, S.; Rodríguez-González, P.; Davis, W. C.; García Alonso, J. I. Development of a Common Procedure for the Determination of Methylmercury, Ethylmercury, and Inorganic Mercury in Human Whole Blood, Hair, and Urine by Triple Spike Species-Specific Isotope Dilution Mass Spectrometry. *Anal. Chem.* **2017**, *89*, 6731–6739.

(41) Krata, A. A.; Wojciechowski, M.; Karasinski, J.; Bulska, E. Comparative Study of High Performance Liquid Chromatography Species-Specific and Species-Unspecific Isotope Dilution Inductively Coupled Plasma Mass Spectrometry. A Case Study of Selenomethionine and the Origin of its Oxidized Form. *Microchem. J.* **2018**, *143*, 416–422.

(42) Lambertsson, L.; Lundberg, E.; Nilsson, M.; Frech, W. Applications of Enriched Stable Isotope Tracers in Combination with Isotope Dilution GC-ICP-MS to Study Mercury Species Transformation in Sea Sediments during in-situ Ethylation and Determination. *J. Anal. At. Spectrom.* **2001**, *16*, 1296–1301.

(43) Snell, J. P.; Quételet, C. R.; Lambertsson, L.; Qvarnström, J. Preparation and Certification of ERM-AE670, a <sup>202</sup>Hg Enriched Methylmercury Isotopic Reference Material. *J. Anal. At. Spectrom.* **2004**, *19*, 1315–1324.

(44) Ishimatsu, R.; Izadyar, A.; Kabagambe, B.; Kim, Y.; Kim, J.; Amemiya, S. Electrochemical Mechanism of Ion Ionophore Recognition at Plasticized Polymer Membrane/Water Interfaces. *J. Am. Chem. Soc.* **2011**, *133*, 16300–16308.

(45) Sobkowski, J.; Jelińska-Kazimierzczuk, M. *Nuclear Chemistry* (in Polish); Adamantan: Warsaw, 2006.