

Quantification of the chiral recognition in electrochemically driven ion transfer across the interface water/chiral liquid

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Abstract

The electrochemically driven transfer of the chiral anions of D- and L-tryptophan across the interface water/chiral liquid (D- or L-menthol) is stereoselective, and it can be used to determine quantitatively the difference in Gibbs energies for the solvation of chiral ions in chiral liquids. The ion transfer can be achieved in a three-phase arrangement where a droplet of the chiral liquid containing decamethylferrocene as the electroactive redox probe is attached to a graphite electrode immersed in the aqueous solution containing the chiral ions. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Chirality and chiral recognition is a phenomenon of fundamental importance as it is linked to the origin and proliferation of life on earth [1]. The stereoselectivity of chemical and biochemical syntheses [2–4] and separations depends on the chiral discrimination of one or the other isomer. Electrochemical reactions can exhibit stereoselectivity when performed in chiral solvents [5], in the presence of chiral supporting electrolytes [5,6], or on electrodes with a chiral surface [7,8].

Recently we have developed a novel method to determine the Gibbs energies of transfer of ions across liquid/liquid interfaces [9–12]. These experiments are similar to those of Compton and coworkers [13–16], who used immobilized droplets of redox active liquids and studied the simultaneous electron and ion transfer at the three-phase junction. This method overcomes certain limitations of the classical electrochemical technique that needs the use of a four-electrode po-

tentiostat and necessarily uses supporting electrolytes in both liquid phases [17]. Our method works with a three-electrode potentiostat and expands considerably the potential window in which the ion transfer can be measured so that ions with standard Gibbs energies of transfer ranging from –34 to 32 kJ/mol are accessible [18] when the nitrobenzene/water interface is considered. The method is also much less restricted to certain organic phases as is shown by the measurement of ion transfer across the *n*-octanol/water interface [19]. Recently we have determined the standard Gibbs energies of transfer of a number of amino acid anions and cations across the water/nitrobenzene interface. As expected, there is no difference in the Gibbs energies for the D- and L-amino acid ions across this interface because none of the interface forming liquids is chiral [20]. Here we report that the electrochemically driven transfer of chiral ions across the interface water/chiral liquid is stereoselective, and it can be used to determine quantitatively the difference in Gibbs energies for the solvation of chiral ions in chiral liquids. We used the electrochemical oxidation of decamethylferrocene (dmfc) dissolved in D- and L-menthol at three-phase arrangement to estimate the energetic differences of ion transfer between the anions of D- and L-tryptophan from water toward D- and L-menthol.

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2. Experimental conditions

For the determination of the Gibbs energy of transfer of the anions of amino acids D- and L-tryptophan a 0.1 mol dm⁻³ solution of decamethylferrocene was prepared by dissolving it in D- and L-menthol. 2 µL of dmfc solution were attached as a droplet to the surface of a paraffin impregnated graphite electrode (PIGE) by help of an Eppendorf-type pipette. The approximate radius of the hemispherical droplet was 0.15 cm. The PIGE was a graphite rod with 0.5 cm diameter and an exposed surface area of 0.2 cm² [21]. The electrode with the attached droplet was immersed into an aqueous electrolyte solution, containing 1 mol/l NaOH and 1 mol/l sodium salt of D- and L-tryptophan, respectively. Between each measurement the PIGE was polished on white paper and the blank was recorded.

All chemicals used were of analytical grade. Decamethylferrocene and amino acids were products of Acrös Organics and Bachem (Heidelberg, Germany), respectively. D-menthol ((1S, 2R, 5S)-2-isopropyl-5-methylcyclohexanol) and L-menthol ((1R, 2S, 5R)-2-isopropyl-5-methylcyclohexanol) were products of Lancaster (Germany) of 99% purity. All chemicals were used without further purification. The water used was Millipore Q. All experiments were carried out at 40 °C.

The electrochemical oxidation of dmfc in the three-phase arrangement was studied utilizing a three electrode potentiostat. Square-wave (SW) voltammetry was used as a working voltammetric method [22]. SW voltammograms were recorded using the electrochemical measuring system µAUTOLAB (Eco-Chemie, Utrecht, Netherlands). An Ag/AgCl/NaCl (saturated solution) reference electrode ($E = 0.200$ V vs SHE) was used and a platinum wire served as auxiliary electrode.

3. Results and discussion

Fig. 1 outlines the experimental arrangement: a droplet of the water immiscible organic liquid (e.g. 2 µl) is attached to a graphite electrode that is immersed in the aqueous solution containing the anions or cations to be transferred. When anions are to be transferred, the

organic liquid contains decamethylferrocene (dmfc) that can be oxidized to decamethylferrocenium cation (dmfc⁺). To maintain charge neutrality, this oxidation is accompanied by the transfer of anions from the aqueous phase to the organic phase. The entire electrode reaction is: $\text{dmfc}_{(\text{o})} + \text{X}_{(\text{w})}^- \rightleftharpoons \text{dmfc}_{(\text{o})}^+ + \text{X}_{(\text{o})}^- + \text{e}^-$. The oxidation starts at the three-phase junction and advances into the droplet [9,23]. Electrochemical techniques, as e.g. SW voltammetry [24], allow determining the formal potential $E_c^{\theta'}$ of the electrochemical system. The formal potential of the electrochemical reaction is the sum of the standard potential of dmfc in the organic phase ($E_{\text{dmfc}^+/\text{dmfc}(\text{o})}^{\theta'}$), the standard potential of ion transfer across the liquid/liquid interface ($\Delta_w^{\circ} \phi_{\text{X}^-}^{\theta}$), and two terms relating to the activity of the anions in the aqueous phase $a_{\text{X}^-(\text{w})}$ and the dmfc activity in the organic phase $a_{\text{dmfc}(\text{o})}^*$:

$$E_c^{\theta'} = E_{\text{dmfc}^+/\text{dmfc}(\text{o})}^{\theta} + \Delta_w^{\circ} \phi_{\text{X}^-}^{\theta} - \frac{RT}{F} \ln(a_{\text{X}^-(\text{w})}) + \frac{RT}{F} \ln\left(\frac{a_{\text{dmfc}(\text{o})}^*}{2}\right). \quad (1)$$

(The equation is valid provided that the concentration of anions in the aqueous phase is large compared to the dmfc concentration in the organic phase [9,10]). The standard potential of ion transfer is linked to the standard Gibbs energy of ion transfer $\Delta G_i^{\theta(w \rightarrow o)}$ by the simple relation:

$$\Delta_w^{\circ} \phi_i^{\theta} = -\frac{\Delta G_i^{\theta(w \rightarrow o)}}{zF}, \quad (2)$$

where z is the charge of the ion and F is the Faraday constant. When the organic phase is not chiral one cannot expect measurable differences in the standard Gibbs energies of transfer of the enantiomers of the chiral ion, however, using a chiral liquid phase, these differences should be detectable. Indeed we found that D- and L-menthol can be used as chiral liquids above their melting points (41 and 43 °C for D- and L-menthol, respectively), and even below, i.e. at 40 °C because a melting point depression due to the dmfc content occurs. Fig. 2 shows the SW voltammograms of D- and L-tryptophan when present in an aqueous solution containing 1 mol/l sodium salt of corresponding tryptophan and

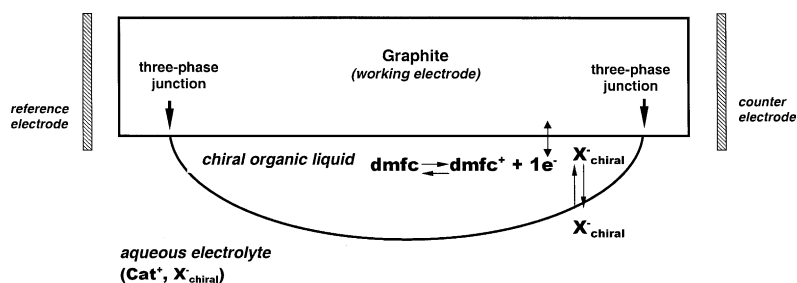


Fig. 1. Schematic representation of the three-phase electrode consisting of a nitrobenzene droplet containing decamethylferrocene (dmfc), which is attached to a graphite electrode and immersed in an aqueous salt solution.

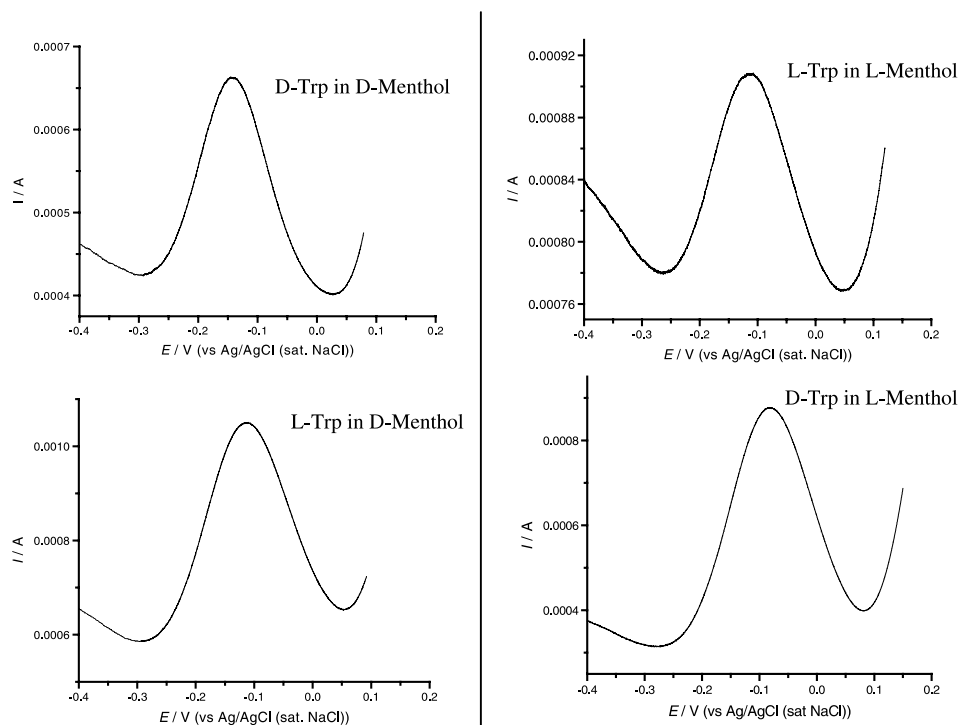


Fig. 2. Square-wave voltammetric responses of D- and L-menthol droplets containing 0.1 mol/l dmfc solution that are attached to a graphite electrode and immersed in aqueous solutions containing 1 mol/l NaOH and 1 mol/l sodium salt of D- and L-tryptophan, respectively. The other conditions were: SW frequency $f = 100$ Hz, SW amplitude $E_{sw} = 50$ mV, and potential scan increment $dE = 0.15$ mV.

1 mol/l NaOH. The forward (oxidation) and backward (reduction) components of the SW voltammetric response were bell-shaped curves with the same peak potentials and heights, as typical for a reversible electrode process (curves are not shown). Furthermore, in cyclic voltammetry, stable responses have been obtained up to ten consecutive cycles, confirming the chemical reversibility of the system. The peak potential of the net SW voltammetric response was linearly dependent on the logarithm of concentration of tryptophan anions within the concentration range from 0.1 to 1 mol dm^{-3} with a slope of about -60 mV in agreement with Eq. (1). Under these conditions the amino acid is present as a single charged anion. From the differences in peak potential, i.e. formal potentials, the energetic differences for the transfer of the two chiral amino acid anions from water to D- and L-menthol can be derived. Fig. 3 gives the $\Delta G_{\text{Trp}^-}^{(w \rightarrow \text{menthol})}$ values at 40°C relative to the $\Delta G_{\text{Trp}^-}^{(w \rightarrow \text{menthol})}$ value of D-tryptophan and D-menthol. The standard deviation of peak potentials was 2 mV, corresponding to the standard deviation of the Gibbs energies of 0.2 kJ mol^{-1} . Since menthol has a rather low dielectric constant (3.98) it is a weakly polar solvent and the energy of transfer of decamethylferrocenium cations from menthol to water is too small to allow the transfer of more hydrophilic amino acid anions than that of tryptophan. In agreement with that, experiments with the aim of transferring phenylalanine, tyrosine, and valine anions failed. Of course it was proved that there is no

measurable difference in Gibbs energies of transfer of D- and L-tryptophan anion from water to the non-chiral nitrobenzene, and also no difference for the transfer of the non-chiral ion perchlorate from water to D- and L-menthol. Note that when more hydrophilic inorganic anions are present in the aqueous phase, e.g. OH^- , Cl^- , SO_4^{2-} , the electrochemical oxidation of dmfc in menthols is accompanied by expulsion of dmfc^+ into water. From the obtained results using D- and L-menthol and D- and L-tryptophan it cannot be excluded that ion pairs of the form $[(\text{dmfc}^+)(\text{D/L-tryp}^-)]$ are formed. Such ion pair formation could diminish the chiral differentiation in the experiment due to a shielding of the chiral anions.

The relative Gibbs energies of transfer given in Fig. 3 show that the transfer of the D-ion to the D-liquid is favored compared to the transfer to the L-liquid. Similarly, it is observed for the L-ion that the transfer to the L-liquid is favored. However, the values for the 4 ion/liquid couples are not symmetric. A possible reason can be that a chiral ion interacts just with one or two of the chiral centers of menthol, possibly even not with the same ones.

4. Conclusions

The obtained results clearly show that the described method can be used to study the recognition of chiral ions and to determine the exact differences in Gibbs free

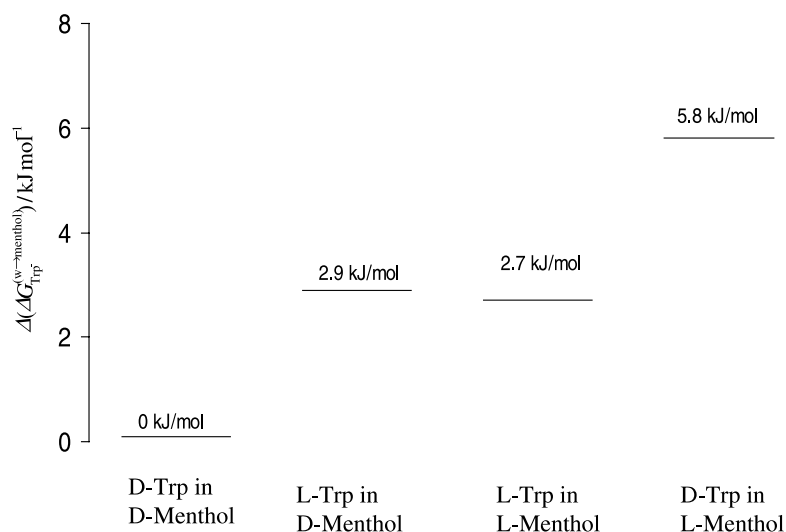


Fig. 3. Schematic representation of the energetic differences of the transfer of D- and L-tryptophan in D- and L-menthol. The ordinate shows the differences of the standard Gibbs energies of transfer $\Delta(\Delta G_{\text{Trp}}^{(w \rightarrow \text{menthol})})$. The values are estimated from the peak potentials of the SW voltammograms depicted in Fig. 2. The data are given relative to the $\Delta G_{\text{Trp}}^{(w \rightarrow \text{menthol})}$ value for D-tryptophan and D-menthol.

energies of transfer of chiral ions from water to a chiral organic phase. Future work must concentrate on finding suitable water immiscible chiral liquids that possess higher dielectric constants than menthol to allow the transfer of more hydrophilic anions than those of D- and L-tryptophan. Further, theoretical studies on the solvation of the chiral ions of D- and L-tryptophan with the chiral liquids D- and L-menthol are necessary to rationalize the obtained experimental results. The chiral recognition demonstrated in this study can be taken as a biomimetic model for the selective transport of chiral ions through a chiral membrane coupled to an energy yielding electron transport.

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