

Study on surface adsorption from cationic surfactant–electrolyte mixed aqueous solution including BF_4^- ion

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Abstract The surface tension of aqueous mixtures of dodecyltrimethylammonium tetrafluoroborate (DTABF_4) and sodium tetrafluoroborate (NaBF_4) was measured as a function of total molality and composition of DTABF_4 at 298.15 K. The results were analyzed by originally developed thermodynamic equations and compared with those of dodecyltrimethylammonium bromide (DTAB)–sodium bromide (NaBr) mixed system. It was indicated that BF_4^- ions reduce the repulsion between DTA^+ ions more effectively than Br^- ions in the adsorbed film. To investigate this difference more closely, the surface tension of DTAB – NaBF_4 and DTABF_4 – NaBr mixed system was also measured. The data analysis revealed that BF_4^- ions are adsorbed positively even for the pure NaBF_4 system and preferentially to Br^- ions in these mixtures. Furthermore, it was concluded that the side-by-side arrangement suggested in the adsorbed film of 1-hexyl-3-methylimidazolium tetrafluoroborate (HMIMBF_4) is due to not only the positive adsorption of BF_4^- ions but also the capability of hydrogen bond formation between imidazolium ion and BF_4^- ions.

Keywords Adsorbed film of ionic surfactant · Surface tension measurement · Adsorption of counterion to surface · Solvation of counterion

Introduction

For past decades, ionic liquids have been received increasing attention as a substitute for existing reaction solvents because of their low vapor pressure, non-flammability, and good solvent ability for a wide range of materials [1–3] and as a novel media for batteries, fuel cells, and solar cells because of their high conductivities and wide electrochemical windows [4–6]. The ionic liquids based of 1-alkyl-3-methylimidazolium ion have been investigated recently as short-chain cationic surfactant in the field of colloid and interface science because the imidazolium cations have an amphiphilic structure and their assembled states are, at least partly, similar to structure of neat ionic liquids [7–11]. We have previously studied the surface property of the aqueous solutions of 1-hexyl-3-methylimidazolium tetrafluoroborate (HMIMBF_4) and a usual cationic surfactant with BF_4^- as its counter anion, dodecyltrimethylammonium tetrafluoroborate (DTABF_4), by employing the surface thermodynamics and X-ray absorption fine structure under total reflection condition (TRXAFS) [12, 13]. It was demonstrated that for example, the surface pressure π vs. the average area per molecule A curve of the HMIMBF_4 system is almost vertical, which suggests an incompressible adsorbed film, at the saturation adsorption whereas those of DTABF_4 and dodecyltrimethylammonium bromide (DTAB) systems show a higher compressibility even at their saturation adsorption (Fig. 1). Furthermore, in the adsorbed film of the HMIMBF_4 –1-hexyl-3-methylimidazolium bromide (HMIMBr) mixture, BF_4^- ions are rather near cations, but Br^- ions are distributed in the electric double layer, and thus, a segregation of BF_4^- and Br^- ions takes place in the adsorbed film [13]. Such counterion distribution is probably examined by employing the theory of Ivanov et al. [14].

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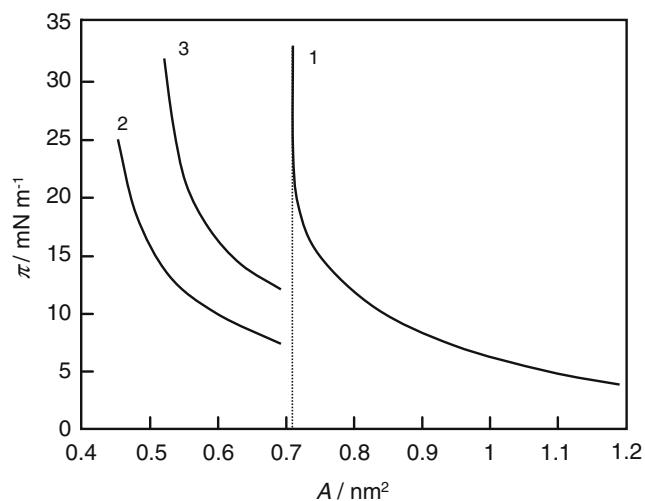


Fig. 1 Surface pressure vs. area per molecule curves: (1) HMIMBF₄, (2) DTABF₄, (3) DTAB

For the neat ionic liquid surface, it is indicated that the BF₄⁻ ion occupies the surface at the same level of the imidazolium ring because the BF₄⁻ ion forms two hydrogen bonds with C(2)-H and -CH on the side chain, and as a result, it positions on top of the imidazolium ring [15–17]. From the fact that the compressibility of the film is very low irrespective of that the observed minimum occupied area of HMIMBF₄ is still larger than the expected area for the fully packed monolayer of HMIM⁺ ions (0.36 nm²), we have concluded that the adsorbed film has similar structure to the neat ionic liquid surface. Probably, the adsorption of imidazolium cations at the air/water interface plays an important role for providing the environment where BF₄⁻ ions are highly concentrated as the neat ionic liquid surface.

In the present study, in order to examine this unique adsorption behavior, we will focus on the effect of the counterions and the role of imidazolium cation on the adsorption behavior. For this purpose, we adopted the dodecyltrimethylammonium ion (DTA⁺ ion) as a surfactant cation which is less capable of forming hydrogen bonds than imidazolium ion and measured the surface tension of the DTABF₄-NaBF₄, DTAB-NaBF₄, and DTABF₄-NaBr systems. It was found that BF₄⁻ ion adsorbs at the air/water interface preferentially to Br⁻ ion, and the capability of hydrogen bond formation between imidazolium ion and counterion works effectively for the side-by-side arrangement in the adsorbed film of HMIMBF₄.

Experimental

Material Sodium tetrafluoroborate (NaBF₄) was purchased from Kanto Kagaku Co., Ltd. (98%) and recrystallized from

water and then baked at 170 °C for 7 h under reduced pressure. Sodium bromide (NaBr) was purchased from Wako Pure Chemical Industries (99.9%) and used as received. DTAB purchased from Wako Pure Chemical Industries (99%) was purified by recrystallizing it five times from the mixture of acetone and ethanol (1:5 volume ratio). DTABF₄ was synthesized from DTAB with equimolar amount of NaBF₄ in the aqueous solution and then recrystallized twice from water. These purities were checked by elemental analysis. Water used for all experiments was distilled three times; the second and third stages were done from alkaline permanganate solution.

Surface tension measurement The surface tension γ of the aqueous solutions was measured by the drop volume method at 298.15 K under atmospheric pressure. The total molality \hat{m} and mole fraction of surfactant \hat{X}_2 were adopted as the experimental concentration variables, where they are defined as

$$\hat{m} = (m_{1+} + m_{1-}) + (m_{2+} + m_{2-}) \quad (1)$$

and

$$\hat{X}_2 = (m_{2+} + m_{2-})/\hat{m} \quad (2)$$

Here, m_{1+} and m_{1-} represent the molalities of cationic and anionic ions dissociated from inorganic salts and m_{2+} and m_{2-} those from ionic surfactants, respectively.

The γ value was calculated by the following equation [18, 19]

$$\gamma = \frac{V \Delta \rho g}{r} F, \quad (3)$$

where V is the volume of a drop, g the local acceleration of gravity, r the capillary radius, and F the correction factor calculated from the following equation,

$$F = 0.1482 + 0.27896 \left(r/V^{1/3} \right) - 0.166 \left(r/V^{1/3} \right)^2 \quad (4)$$

and is $\Delta \rho$ the density difference between air and aqueous solution. The densities of aqueous solutions of NaBr and NaBF₄ ρ_{solution} were measured by the oscillating tube method (Anton Par, D60/602) and shown in Fig. 2. It was found that ρ_{solution} increases linearly with molality as

$$\rho_{\text{solution}} = \rho_{\text{water}} + a\hat{m} \quad (5)$$

where ρ_{water} was 0.997047 g cm⁻³, and $a = 7.65052 \times 10^{-5}$ (NaBr) 6.69881×10^{-5} (NaBF₄), respectively.

The experimental error of the surface tension measurement was within 0.05 mN m⁻¹.

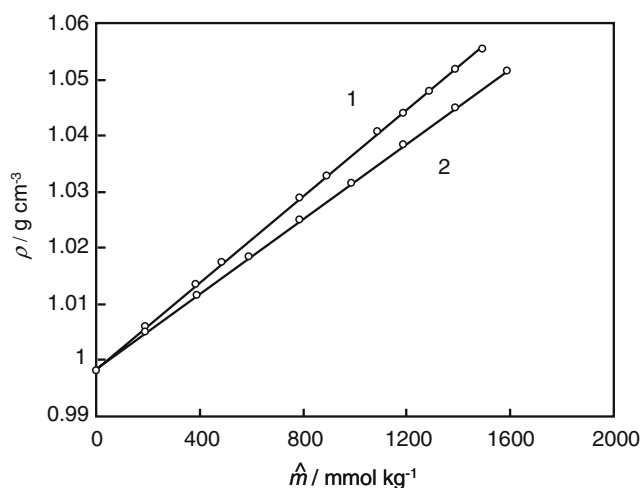


Fig. 2 Density of aqueous solution vs. molality curves: (1) NaBr, (2) NaBF₄

Result and discussion

The results of surface tension measurements of the aqueous solutions of the DTABF₄–NaBF₄ mixtures were plotted against \hat{m} at fixed mole fractions of DTABF₄ \hat{X}_2 in Fig. 3. The γ value decreases with increasing \hat{m} and the shape of γ vs. \hat{m} changes regularly with \hat{X}_2 . We have previously proved that the break points on these curves are corresponding to the phase transition of the adsorbed film from the gaseous to the expanded states [20]. It should be noted that the γ values of the aqueous solution of NaBF₄ slightly decreases with \hat{m} , in contrast to that of NaBr, as shown in the wide concentration ranges in Fig. 4.

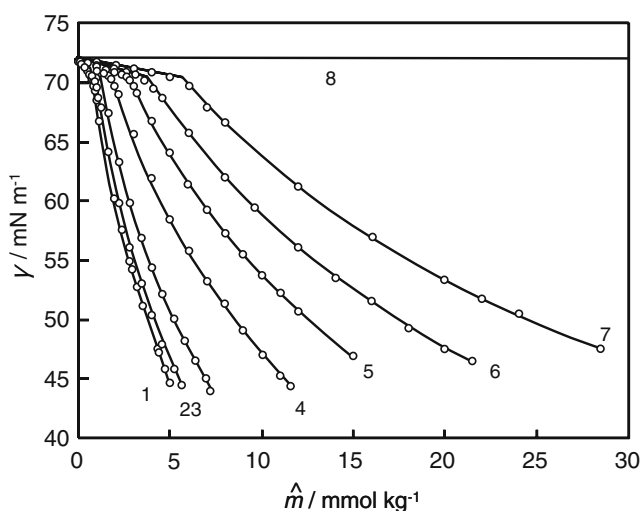


Fig. 3 Surface tension vs. total molality curves of DTABF₄–NaBF₄ system at constant bulk compositions: (1) $\hat{X}_2 = 1$ (DTABF₄), (2) 0.8, (3) 0.5, (4) 0.2, (5) 0.1, (6) 0.05, (7) 0.03, (8) 0 (NaBF₄)

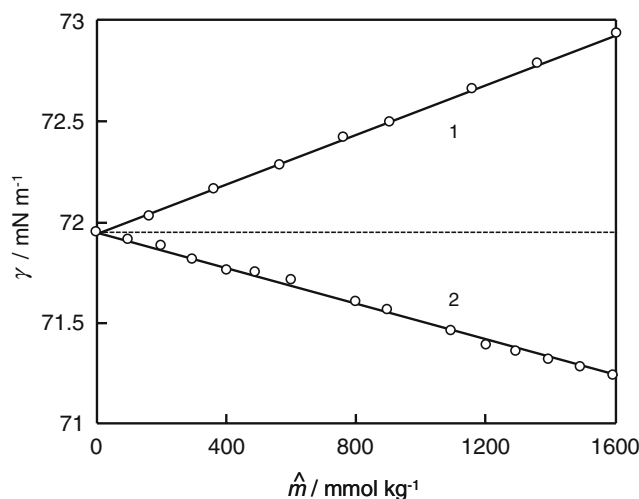


Fig. 4 Surface tension vs. molality curves of electrolyte solutions: (1) NaBr, (2) NaBF₄

The total differential of surface tension at constant temperature and pressure is given by [21]

$$d\gamma = -\left(\frac{RT\hat{\Gamma}^H}{\hat{m}}\right)d\hat{m} - \left(\frac{RT\hat{\Gamma}^H}{2\hat{X}_1\hat{X}_2}\right) \times \left(\hat{X}_2^H - \hat{X}_2\right)d\hat{X}_2 \tag{6}$$

where the total surface density of ions and the surface composition of the second surfactant, DTABF₄, are defined as

$$\hat{\Gamma}^H = \Gamma_{DTA^+}^H + \Gamma_{Na^+}^H + \Gamma_{BF_4^-}^H = 2(\Gamma_{DTA^+}^H + \Gamma_{Na^+}^H) \tag{7}$$

where the electroneutrality condition $\Gamma_{DTA^+}^H + \Gamma_{Na^+}^H = \Gamma_{BF_4^-}^H$ is taken into account, and

$$\hat{X}_2^H = 2\Gamma_{DTA^+}^H / \hat{\Gamma}^H \tag{8}$$

respectively. From Eq. (6), the surface density of surfactant was calculated by using

$$\hat{\Gamma}^H = -(\hat{m}/RT) \left(\frac{\partial\gamma}{\partial\hat{m}}\right)_{T,p,\hat{X}_2} \tag{9}$$

and shown in Fig. 5. From the linear decrease of γ with \hat{m} for the pure NaBF₄ solution, it was noticed that NaBF₄ adsorbs positively at the air/water interface, and its amount increases with increasing \hat{m} . It is well known that Na⁺ ion shows negative adsorption due to the image force from the interface; hence, it was revealed that BF₄[−] ion adsorbs positively in the pure NaBF₄ system. On the other hand, $\hat{\Gamma}^H$ of DTABF₄ and the mixtures increases with increasing \hat{m} and shows the discontinuous change at the phase transition concentrations.

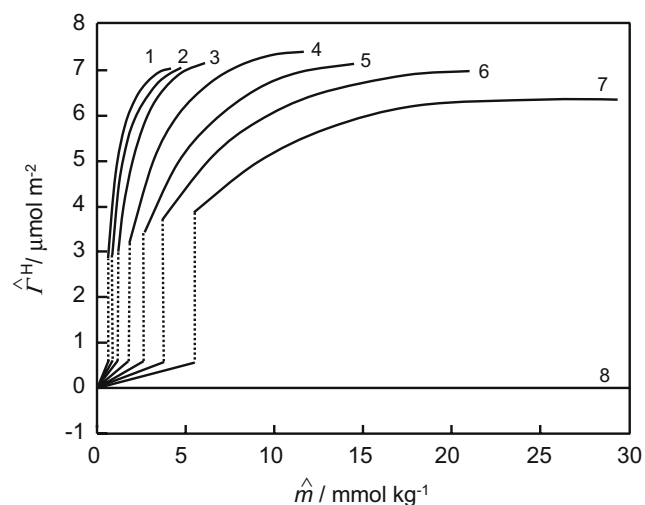


Fig. 5 Total surface density vs. total molality curves of DTABF₄–NaBF₄ system at constant bulk compositions: (1) $\hat{X}_2 = 1$ (DTABF₄), (2) 0.8, (3) 0.5, (4) 0.2, (5) 0.1, (6) 0.05, (7) 0.03, (8) 0 (NaBF₄)

Next, let us evaluate the compositions of DTABF₄ in the adsorbed film \hat{X}_2^H by plotting \hat{m} values against \hat{X}_2 at fixed γ and then applying

$$\hat{X}_2^H = \hat{X}_2 - \left(2\hat{X}_1\hat{X}_2 / \hat{m} \right) \left(\partial\hat{m} / \partial\hat{X}_2 \right)_{T,p,\gamma} \quad (10)$$

to the \hat{m} vs. \hat{X}_2 curves. The results were drawn in the form of the phase diagram of adsorption (PDA) in which the composition in the bulk solution and that in the adsorbed film were represented together (Fig. 6).

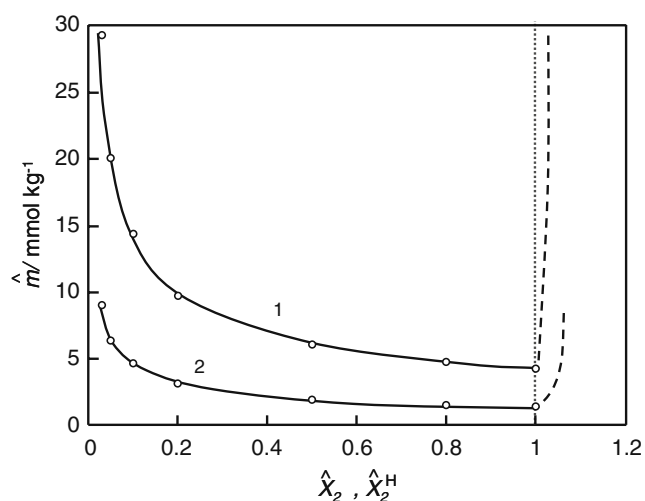


Fig. 6 Total molality vs. composition curves of DTABF₄–NaBF₄ system at constant surface tensions: (1) $\gamma = 47.5 \text{ mN m}^{-1}$, (2) $\gamma = 65 \text{ mN m}^{-1}$; solid line \hat{m} vs. \hat{X}_2 , broken line \hat{m} vs. \hat{X}_2^H

It is worth noting that the value of \hat{X}_2^H is larger than unity in the whole bulk composition range. Considering that \hat{X}_2^H is rewritten from (Eqs. 7 and 8) as

$$\hat{X}_2^H = \frac{\Gamma_{\text{DTA}^+}^H}{\Gamma_{\text{DTA}^+}^H + \Gamma_{\text{Na}^+}^H} \quad (11)$$

it can be understood that one of the reason for this is the negative value of $\Gamma_{\text{Na}^+}^H$, that is, exclusion of Na⁺ ions from the surface region by the electrostatic repulsion toward DTA⁺ ions adsorbed at the interface. Figure 7 represents the surface densities of DTA⁺ ion evaluated by combining the $\hat{\Gamma}^H$ values in Fig. 5 and \hat{X}_2^H values in Fig. 6, where the results of the DTAB–NaBr system [22] is also drawn. The $\Gamma_{\text{DTA}^+}^H$ value increases with decreasing \hat{X}_2 , but its dependence on \hat{X}_2 is much weaker than that observed in the DTAB–NaBr mixtures. These results clearly demonstrate that the shielding effect of BF₄[−] ion on the electrostatic repulsion between DTA⁺ ions is quite effective compared with that of Br[−] ion, and the electric charge of DTA⁺ ions is almost completely shielded even in the pure DTABF₄ system. Therefore, the further adsorption of BF₄[−] ion does not take place when NaBF₄ is added.

Furthermore, the investigation of adsorption behavior of the DTAB–NaBF₄ system revealed that BF₄[−] ion adsorbs at the air/water interface preferentially to Br[−] ion as follows. Figures 8 and 9 show the γ vs. \hat{m} curves and the PDA for the DTAB–NaBF₄ mixtures. It should be noted in Fig. 8 that the γ vs. \hat{m} curve at a given \hat{X}_2 moves to the left from $\hat{X}_2 = 1$ (DTAB) to $\hat{X}_2 = 0.5$ and then turns to the right with decreasing \hat{X}_2 . The \hat{m} vs. \hat{X}_2 curves at given surface tensions (solid curves in Fig. 9) demonstrates this situation more clearly; the curves have a minimum at around $\hat{X}_2 = 0.5$.

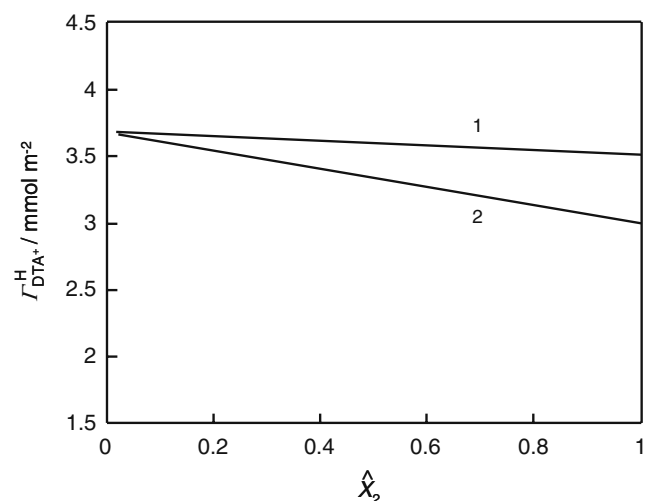


Fig. 7 Surface density of DTA⁺ ion vs. bulk composition at $\gamma = 47.5 \text{ mN m}^{-1}$: (1) DTABF₄–NaBF₄, (2) DTAB–NaBr

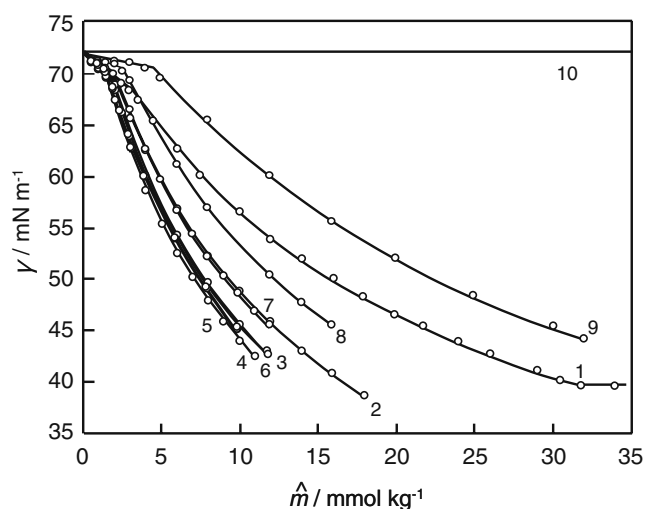


Fig. 8 Surface tension vs. total molality curves of DTAB–NaBF₄ system at constant bulk compositions: (1) $\hat{X}_2 = 1$ (DTAB), (2) 0.9, (3) 0.8, (4) 0.65, (5) 0.5, (6) 0.352, (7) 0.2, (8) 0.1, (9) 0.03, (10) 0 (NaBF₄)

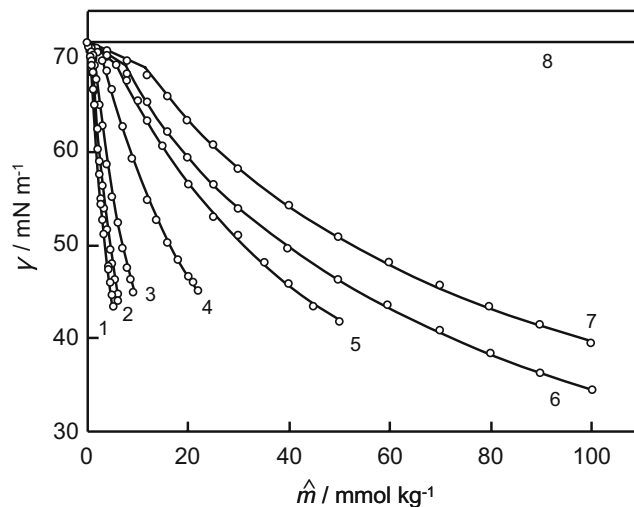


Fig. 10 Surface tension vs. total molality curves of DTABF₄–NaBr system at constant bulk compositions: (1) $\hat{X}_2 = 1$ (DTABF₄), (2) 0.8, (3) 0.5, (4) 0.2, (5) 0.1, (6) 0.05, (7) 0.03, (8) 0 (NaBr)

The \hat{X}_2^H values calculated from the solid curves are shown by the broken lines, which form the PDA together with the \hat{m} vs. \hat{X}_2 curves. There are two important points. First, the PDA exhibits a negative azeotropic point, and thus, two components are mixed favorably in the adsorbed film in the whole range of \hat{X}_2 . Secondly the \hat{X}_2^H values are around $\hat{X}_2^H = 0.5$ irrespective of \hat{X}_2 when $\hat{X}_2 < 0.5$. Taking account of the relation $\hat{X}_2^H = X_{DTA^+}^H + X_{Br^-}^H$ from (Eq. 8) and

$$X_{Na^+}^H + X_{DTA^+}^H + X_{BF_4^-}^H + X_{Br^-}^H = 1 \quad (12)$$

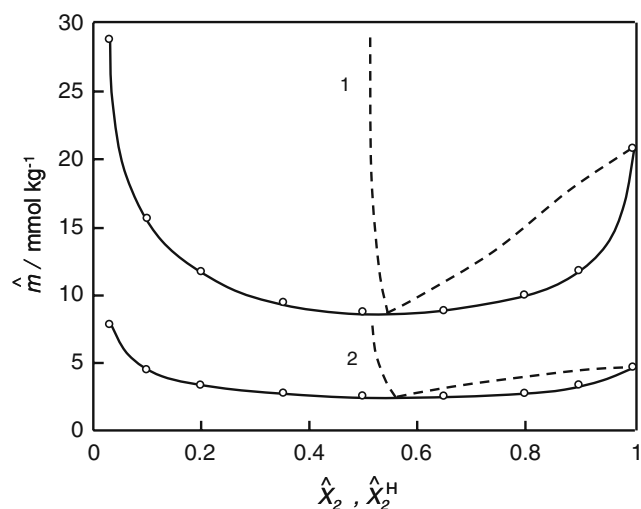


Fig. 9 Total molality vs. composition curves of DTAB–NaBF₄ system at constant surface tensions: (1) $\gamma = 46 \text{ mN m}^{-1}$, (2) $\gamma = 65 \text{ mN m}^{-1}$; solid line \hat{m} vs. \hat{X}_2 , broken line \hat{m} vs. \hat{X}_2^H

and supposing that $X_{Na^+}^H \approx 0$, we have $X_{DTA^+}^H + X_{Br^-}^H = 0.5$ and $X_{BF_4^-}^H = 0.5$ when $\hat{X}_2^H = 0.5$. Therefore, the electroneutrality condition $X_{DTA^+}^H = X_{BF_4^-}^H + X_{Br^-}^H$ yields $X_{Br^-}^H = 0$; it is suggested that the adsorbed film is almost composed of DTA⁺ and BF₄⁻ ions when $\hat{X}_2 < 0.5$. This is demonstrated more precisely by combining the results of the DTAB–NaBF₄ system with those of the DTABF₄–NaBr system as shown later.

We have previously reported that the Br⁻ ions in the adsorbed film of DTAB aqueous solution have two hydration states by the TRXAFS measurement [12]: one

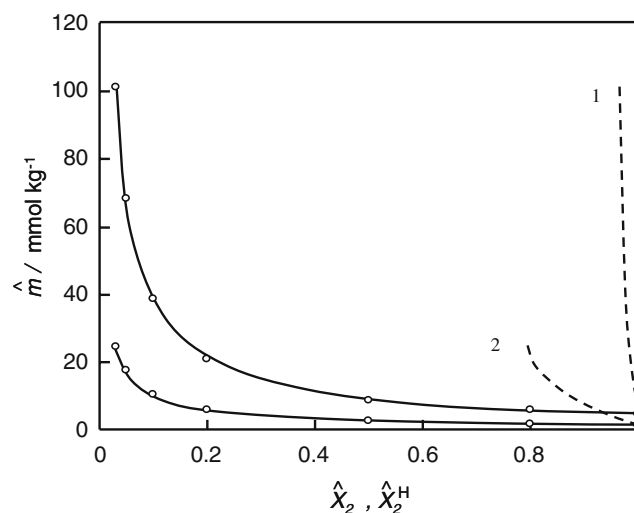


Fig. 11 Total molality vs. composition curves of DTABF₄–NaBr system at constant surface tensions: (1) $\gamma = 46 \text{ mN m}^{-1}$, (2) $\gamma = 65 \text{ mN m}^{-1}$; solid line \hat{m} vs. \hat{X}_2 , broken line \hat{m} vs. \hat{X}_2^H

Table 1 Surface compositions of ions at $\hat{X}_2 = 0.5$

$\gamma/\text{mN m}^{-1}$	$X_{\text{DTA}^+}^{\text{H}}$	$X_{\text{Na}^+}^{\text{H}}$	$X_{\text{BF}_4^-}^{\text{H}}$	$X_{\text{Br}^-}^{\text{H}}$
65	0.525	-0.0250	0.455	0.0450
46	0.515	-0.0150	0.475	0.0250

corresponding to the Br^- ions with smaller hydration number of 3 to 4 distributed near the surfactant head groups (bound ions) and the other the Br^- ions with hydration number of 6 similar to those in the bulk solution (free ions). The fraction of the free ions decreases with increasing $I_{\text{DTA}^+}^{\text{H}}$, and the fraction of the bound ions increases instead. However, in the mixed adsorbed film of HMIMBF₄–HMIMBr system, the TRXAFS revealed that the Br^- ions are all in the free states at almost all the bulk compositions [13]. Taking these results into consideration, it is indicated that the fraction of the bound BF_4^- is considerably high even in the pure DTABF₄ system, and Br^- ions distribute mainly in the electrical double layer as the free ion.

Finally, let us calculate the ratio of BF_4^- ion and Br^- ion in the mixed adsorbed film. Here, it should be remembered that the surface densities of the respective ions cannot be calculated in principle for the binary ionic surfactant mixture without common ions like the DTAB–NaBF₄ system [21]. However, they can be evaluated at $\hat{X}_2 = 0.5$ by combining the results of the DTABF₄–NaBr system as follows. Figures 10 and 11 show the γ vs. \hat{m} curves and the PDA for the DTABF₄–NaBr mixtures. The γ vs. \hat{m} curve gradually changes its position from $\hat{X}_2 = 1$ (DTABF₄) by adding NaBr, which gives the similar feature to that of the DTABF₄–NaBF₄ mixture in Fig. 3, but the different one from that of the DTAB–NaBF₄ mixture in Fig. 8. Since the numbers of constituent ions are the same for the DTABF₄–NaBr and DTAB–NaBF₄ systems at a given \hat{m} and at $\hat{X}_2 = 0.5$, we have four equations: the one is Eq. (12) from the mass balance relation, and other three are

$$\hat{X}_2^{\text{H}} = X_{\text{DTA}^+}^{\text{H}} + X_{\text{Br}^-}^{\text{H}} \quad (\text{DTAB} - \text{NaBF}_4 \text{ system}) \quad (13)$$

$$\hat{X}_2^{\text{H}} = X_{\text{DTA}^+}^{\text{H}} + X_{\text{BF}_4^-}^{\text{H}} \quad (\text{DTABF}_4 - \text{NaBr system}) \quad (14)$$

and

$$X_{\text{DTA}^+}^{\text{H}} + X_{\text{Na}^+}^{\text{H}} = X_{\text{BF}_4^-}^{\text{H}} + X_{\text{Br}^-}^{\text{H}} \quad (15)$$

from the electroneutrality condition in adsorbed film. The $X_{\alpha}^{\text{H}}(\alpha; \text{DTA}^+, \text{Na}^+, \text{Br}^-, \text{BF}_4^-)$ values thus estimated are listed at $\gamma=65$ and 46 mN m^{-1} in Table 1. It is evident that the ratio $X_{\text{Br}^-}^{\text{H}}/X_{\text{BF}_4^-}^{\text{H}} = 0.009$ and 0.053 , and thus, the adsorbed film is almost composed of DTA^+ and BF_4^- ions when $\hat{X}_2 = 0.5$. This is in accord with the suggestion

obtained from the PDA of the DTAB–NaBF₄ system and the examination on it by supposing $X_{\text{Na}^+}^{\text{H}} \approx 0$.

In the present study, for the purpose of examining the side-by-side arrangement of HMIMBF₄ in the adsorbed film, we investigated the counterion effect on surface adsorption of the several cationic surfactants. The important conclusions are as follows: BF_4^- ions show strong shield effect on the electric repulsion between surfactant ions, and they are preferentially adsorbed at the air/water interface even when the bulk solutions are enriched with Br^- ion. Taking into account that the BF_4^- ion adsorbs positively while Br^- ion negatively at the air/water interface in the respective pure inorganic electrolyte solutions, the differences in adsorption behavior observed in the binary mixtures of DTABF₄–NaBF₄, DTAB–NaBF₄, and DTABF₄–NaBr are partially attributable to the difference in surface activity of the counterions. Although the adsorption ability of BF_4^- ion is undoubtedly important factor in governing the adsorption behavior of cationic surfactant having BF_4^- as counter anion, the interaction between the surfactant cation and BF_4^- is also essential in the adsorption behavior. For example, the side-by-side arrangement is suggested due to the ion paring between HMIM⁺ and BF_4^- ions in the adsorbed film, whereas DTABF₄ itself does not show such arrangement as examined from the π vs. A curves (Fig. 1). Therefore, it is indicated that the capability of hydrogen bond formation between imidazolium ion and counterion works effectively for the side-by-side arrangement.

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