The Nature of the Micellar Stern Region As Studied by Reaction Kinetics. 21†

Niklaas J. Buurma,§ Paola Serena,§ Michael J. Blandamer,† and Jan B. F. N. Engberts*,§

Physical Organic Chemistry Unit, Stratingh Institute, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands, and Department of Chemistry, University of Leicester, Leicester, LE1 7RH, United Kingdom

j.b.f.n.engberts@chem.rug.nl

Received January 6, 2004

The nature of rate-retarding effects of cationic micelles on the water-catalyzed hydrolyses of a series of para-substituted 1-benzoyl-1,2,4-triazoles (1a–f) and 1-benzoyl-3-phenyl-1,2,4-triazole (2) has been studied using kinetic methods. A comparison is drawn between medium effects in the micellar Stern region and in model solutions for the micellar Stern region. Simple model solutions involving concentrated aqueous solutions of a small ionic molecule resembling the surfactant headgroup, as reported before,3 were improved. New model solutions for alkyltrimethylammonium bromide micelles contain both tetramethylammonium bromide (TMAB), mimicking micellar headgroups, and 1-propanol, mimicking hydrophobic tails. The rate-retarding effect of micelles on the hydrolysis of 1a–f and 2 is caused by the high concentration of headgroups as well as by hydrophobic tails in the Stern region where 1a–f and 2 bind to the micelle. Individual contributions of these interactions are quantified. Rate-retarding effects found for different probes, with different sensitivities for interactions as they occur when the probe binds to the micellar Stern region, as well as the micellar Stern region’s micropolarity as reported by the E2(30) probe, are satisfactorily reproduced by new model solutions containing both TMAB and 1-propanol.

Introduction

Micelle-forming surfactants self-aggregate in a cooperative manner, forming stable but highly dynamic clusters above the critical micelle concentration (cmc). Gruen described a realistic model for a micelle2 which involves a rather sharp interface between two distinctly different “zones” making up a micelle: (i) a dry2,3 hydrophobic hydrocarbon core surrounded by (ii) a region filled with surfactant headgroups, part of the counterions (in case of ionic surfactants) and water, viz. the Stern region. The Stern region is an interfacial region between the hydrocarbon core and bulk water (the third “zone” in micellar solutions). This model has been validated for both ionic and nonionic micelles using molecular dynamics simulations.4,5

In micellar solutions, reactions can be either accelerated or inhibited compared to the reaction in aqueous solutions without added cosolutes.6–8 Remarkable success in enhancing reaction rates9 introducing catalytic moieties in surfactants has been achieved.10 However, we limit discussion solely to “medium effects” as they occur in solutions of unfunctionalized micelle-forming amphiphiles.

The exact mechanism of micellar acceleration and deceleration has remained obscure because a good description of the local reaction environment offered by micellar binding sites, often referred to as the “micellar pseudophase”, is lacking. The present (and our previous1) study investigated mechanistic aspects of micellar effects on water-catalyzed hydrolysis reactions to develop a satisfactory description of the micellar pseudophase as a reaction medium. Nevertheless, the distinct differences between micellar core and Stern region make it impossible to describe the complete micelle as a homogeneous “entity” or “(pseudo)phase”. Descriptions of medium effects exerted by micelles describe either the Stern region or the hydrocarbon core, depending on the binding location of the (reactive) probes that are used.

† University of Groningen.
§ University of Leeds. E-mail: mjb@le.ac.uk.
(9) The difference between reaction rates and reaction rate constants should be noted. Due to compartmentalization, concentrations of reactants inside micelles can be higher so that, notwithstanding lower reaction rate constants, reaction rates can still be higher than observed in bulk water.
A prerequisite for understanding the reaction medium offered by micelles is to know where reaction occurs. A micelle offers several binding sites for relatively apolar molecules. These include the hydrophobic core and hydrophobic binding sites located in the Stern region. The latter region is particularly flexible in binding molecules as it contains, apart from water molecules, highly hydrophilic surfactant headgroups and hydrophobic domains due in part to backfolding of surfactant tails.1-3

In our previous study,1 we showed that the water-catalyzed hydrolysis reactions of activated amides take place in the micellar Stern region. This conclusion agrees with the binding locations found using a variety of techniques for many other, especially aromatic, molecules.11

In view of the literature evidence mentioned above, the kinetic probes used in the study reported here almost certainly bind in the micellar Stern region. Hence, the experiments effectively provide information about the reaction medium properties of the Stern region. The aim of this study was to model the medium properties of the micellar Stern region in terms of aqueous solutions comprising compounds mimicking molecules and parts of molecules present in the Stern region.

A key feature of the micellar Stern region is the concentration of headgroups and counterions. The concentration of headgroups in the Stern region12-14 lies in the range of 3-5 mol dm-3, though recent work suggested lower values.15 In our previous work, we determined upper limits for the concentration of headgroups in the Stern regions of n-dodecyltrimethylammonium bromide (DTAB), n-hexadecyldimethylammonium bromide (CTAB), and sodium n-dodecyl sulfate (SDS) of approximately 4 M.1 The concentration of counterions is slightly less due to incomplete counterion binding, locally creating an electrically nonneutral environment.

In our preceding study,1 we showed that rate-retarding effects exerted by micelles on certain hydrolysis reactions can be largely explained in terms of salt effects. However, the success of modeling the micellar Stern region using a concentrated salt solution depends on the reaction chosen to probe the Stern region’s properties as a reaction medium.1,16 In this study we incorporate in the mimic both polar and apolar components with the aim of inducing medium effects still more representative of the Stern region.

A Kinetic Model for Reactions in Micellar Solutions

The hydrolytic reactions described here are the water-catalyzed, pH-independent hydrolysis reactions of substituted 1-benzoyl-1,2,4-triazoles (1a-f) and 1-benzoyl-3-phenyl-1,2,4-triazole (2).

The reactions proceed via a dipolar activated complex in which two water molecules, one acting as a nucleophile and the other as a general base, are involved with three protons in flight (Scheme 1).

The reactions proceed via a dipolar activated complex in which two water molecules, one acting as a nucleophile and the other as a general base, are involved with three protons in flight (Scheme 1).17-19

Kinetic data for reactions in micellar solutions are analyzed using eq 1 in a nonlinear least-squares fitting procedure. Equation 1 represents the nonlinear form of the Menger–Portnoy equation:

\[
k_{\text{obsd}} = \frac{k(_{\text{mic}})K_{m}([\text{surf}] - \text{cmc})/N}{1 + k_{m}([\text{surf}] - \text{cmc})/N}
\]

Here \(k_{\text{obsd}}\) is the observed rate constant at a surfactant concentration \([\text{surf}]\), \(k_{m} = 0\) is the rate constant in water without added cosolute (pH = 4.0),23 and \(K_{m}\) is the rate constant under conditions of complete binding of the substrate to the micelles. For the present system, the micellar rate constant \(K_{m}\) is the rate constant for reaction in the micellar Stern region. \(N\) is the aggregation number of the micelle, \(K_{m}\) is the binding constant of the kinetic probe to the micelle (the kinetic probe residing in the Stern region), and \(N\) is the critical micelle concentration of the surfactant.

In addition to micellar rate constants \(K_{m}\) and micellar binding constants \(K_{m}\), transition-state pseudoequilibrium constants \(K_{AC}\) can be determined.22,23 Transition-state pseudoequilibrium constants \(K_{AC}\) are hypothetical bind-


\(21\) For the present reactions, the minor decrease in rate constant before the cmc indicates that rate-retarding effects below the cmc are small, justifying our choice of \(k_{m} = 0\). It should also be noted that micellar rate constants for substrates bound to spherical micelles can only be determined as long as the surfactant concentration is below the concentration at which wormlike micelles start to form. This poses an upper limit on the concentration range in which relevant results can be obtained.


ing constants of the activated complex to the micelle. For the system under study, \( K^{AC} \) is given by eq 2.

\[
K^{AC} = \frac{k_{mic}K_m}{k_m(1 - \theta)} = \frac{k_{mic}[H_2O]_m^2}{k_m[H_2O]^2} \]  

In eq 2, \( k_w' \) and \( k_{mic}' \) are the third-order rate constants (rate of reaction of probe \( P \): \( \frac{d[P]}{dt} = k_w'[P][H_2O]^2 \), where \( z \) represents subscripts mic and w in eq 2) in bulk water and in the micellar Stern region, respectively. \([H_2O]_w\) is the water concentration in micellar solutions. This lower polarity is envisaged to be primarily caused by interactions of the probes with the hydrophobic tails of the surfactants in the Stern region.

In this context, we chose the hydrolysis of a series of substituted 1-benzoyl-1,2,4-triazoles 1a–f to investigate the presence of micelles of DTAB and CTAB for detailed analysis. The Stern region of micelles of ionic surfactants is modeled by including both hydrophobic and ionic interactions. As we separate the effect of the ionic headgroups and of the hydrophobic tails leading to a satisfactory reproduction of the behavior of all tested probes. It should be noted that ionic interactions do not only include the effect of the charges of the surfactant headgroups but instead are defined to include all rate-influencing effects of the surfactant headgroups, i.e. charge, effect on local water activity, and direct 1:1 interactions with the hydrolytic probe.

**Results and Discussion**

Rate constants for hydrolysis of 1a–f in water without added cosolutes, \( k_m(1 - \theta) \), together with the Hammett substituent constants \( \alpha_p \) are summarized in Table 1 (superscript \( x \) indicates the probe molecule).

Table 1. Overview of the Hydrolysis Rate Constants of 1-Benzoyl-1,2,4-triazoles 1a–f at 298.15 K

<table>
<thead>
<tr>
<th>probe</th>
<th>( \alpha_p )</th>
<th>( k_m(1 - \theta) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>-0.28</td>
<td>4.1</td>
</tr>
<tr>
<td>1b</td>
<td>-0.14</td>
<td>9.4</td>
</tr>
<tr>
<td>1c</td>
<td>0.00</td>
<td>21.2</td>
</tr>
<tr>
<td>1d</td>
<td>0.24</td>
<td>36.0</td>
</tr>
<tr>
<td>1e</td>
<td>0.32</td>
<td>43.1</td>
</tr>
<tr>
<td>1f</td>
<td>0.81</td>
<td>278</td>
</tr>
</tbody>
</table>

It is shown that the rate of hydrolysis increases with increasing electron-withdrawing ability of the para-substituent, as expected for a reaction in which a (partial) negative charge develops on the carbonyl group going toward the activated complex (Scheme 1). The hydrolysis of all of these probes is retarded in solutions containing micelles of CTAB and DTAB (examples given in Figure 1).

From a nonlinear least-squares fit to eq 1, micellar rate constants for hydrolysis and micellar binding constants were determined (Table 2).

There is no appreciable trend in the micellar binding constants of 1a–f (Table 2) with substituent constant (Table 1). However, micellar binding constants for CTAB on average are about three times larger than those for DTAB. For comparison of the rate-retarding effects on the hydrolysis of the individual hydrolytic probes, the relative rate constants of hydrolysis in aqueous solutions of DTAB and CTAB and the logarithms of these relative rate constants are given in Table 3.

For 1d–f, micelles of CTAB retard hydrolysis more than micelles of DTAB. However, micelles of DTAB retard the hydrolysis of 1a,b more compared with micelles of CTAB (Table 3). Apart from these rather unusual rate effects, \( \ln(k_{mic}/k_m(1 - \theta)) \) tends to increase (decrease in absolute value) with increasing \( \alpha_p \).

We improved our previous model for the micellar Stern region by adding a compound mimicking the interactions with the alkyl tails of the surfactants. 1-Propanol was used as added cosolvent being the highest linear alcohol.

---

(26) In our opinion, the conclusion in ref 25 that the rate-retarding effect brought about by the micelles is not a salt effect is unwarranted. The conclusion has been made on activation parameters of the reaction occurring in the micelle. However, these activation parameters will include effects of the thermodynamics of micellization changing with temperature.
(28) Recently, similar attempts at including both "headgroup mimics" and "tail mimics" in model solutions for the micellar Stern region have been made. However, these tertiary solutions either (i) do not distinguish between the rate effects of headgroup mimic and tail mimic (refs 25 and 40) or (ii) seem to reproduce the rate of a single reaction only (Tada, E. B.; Ouarti, N.; Silva, P. L.; Blagoeva, I. B.; El Seoud, O. A.; Ruasse, M.-F.; Langmuir 2003, 19, 10666–10672).

---
completely miscible with water at 298.15 K. In addition, widely accepted micelle models suggest that on average about 2–3 methylene units are in contact with water. The effects of ionic headgroups and alkyl tails as mimicked by TMAB and 1-propanol, respectively, have to be distinguished. Ideally, trends in sensitivity toward the icked by TMAB and 1-propanol, respectively, have to be studied. By analogy with presence of these two compounds should be different.

FIGURE 1. Rate constants of hydrolysis of 1c at 298.15 K in solutions containing micelles of DTAB (left) and CTAB (right).

TABLE 2. Overview of Micellar Rate Constants of Hydrolysis and Micellar Binding Constants a of Para-Substituted 1-Benzoyl-1,2,4-triazoles 1a–f at 298.15 K

<table>
<thead>
<tr>
<th>Compound</th>
<th>$k_{r,CTAB}/10^{-4} \text{s}^{-1}$</th>
<th>$k_{r,DTAB}/10^{-4} \text{s}^{-1}$</th>
<th>$K_{f,CTAB}/10^3 \text{dm}^3 \text{mol}^{-1}$</th>
<th>$K_{f,DTAB}/10^3 \text{dm}^3 \text{mol}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>0.34 ± 0.03</td>
<td>0.25 ± 0.04</td>
<td>9.3 ± 0.3</td>
<td>3.1 ± 0.2</td>
</tr>
<tr>
<td>1b</td>
<td>0.70 ± 0.08</td>
<td>0.70 ± 0.06</td>
<td>10.3 ± 0.4</td>
<td>3.4 ± 0.1</td>
</tr>
<tr>
<td>1c</td>
<td>2.5 ± 0.2</td>
<td>2.4 ± 0.3</td>
<td>3.44 ± 0.07</td>
<td>1.5 ± 0.1</td>
</tr>
<tr>
<td>1d</td>
<td>5.4 ± 0.2</td>
<td>6.67 ± 0.10</td>
<td>13.9 ± 0.4</td>
<td>4.2 ± 0.1</td>
</tr>
<tr>
<td>1e</td>
<td>7.0 ± 0.1</td>
<td>8.4 ± 0.2</td>
<td>21.0 ± 0.3</td>
<td>6.0 ± 0.1</td>
</tr>
<tr>
<td>1f</td>
<td>67 ± 3</td>
<td>74 ± 12</td>
<td>6.4 ± 0.3</td>
<td>1.4 ± 0.2</td>
</tr>
</tbody>
</table>

 a CMCs set to 0.9 and 14.0 mM for CTAB and DTAB, respectively. These are the average values of the CMCS determined from initial curve-fitting with unrestricted CMCS.

TABLE 3. Relative Rate Constants of Hydrolysis of 1a–f Taking Place in Micelles of DTAB and CTAB at 298.15 K

<table>
<thead>
<tr>
<th>Compd</th>
<th>$k_{r,DTAB}/k_{r,CTAB}$ (m = 0)</th>
<th>$\ln[k_{r,DTAB}(m_c = 0)/k_{r,CTAB}(m_c = 0)]$</th>
<th>$k_{r,DTAB}/k_{r,CTAB}$ (m = 0)</th>
<th>$\ln[k_{r,DTAB}(m_c = 0)/k_{r,CTAB}(m_c = 0)]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>0.08</td>
<td>$-2.5 ± 0.1$</td>
<td>0.06</td>
<td>$-2.8 ± 0.2$</td>
</tr>
<tr>
<td>1b</td>
<td>0.08</td>
<td>$-2.5 ± 0.1$</td>
<td>0.07</td>
<td>$-2.6 ± 0.1$</td>
</tr>
<tr>
<td>1c</td>
<td>0.12</td>
<td>$-2.14 ± 0.06$</td>
<td>0.12</td>
<td>$-2.1 ± 0.3$</td>
</tr>
<tr>
<td>1d</td>
<td>0.15</td>
<td>$-1.90 ± 0.04$</td>
<td>0.19</td>
<td>$-1.68 ± 0.02$</td>
</tr>
<tr>
<td>1e</td>
<td>0.16</td>
<td>$-1.82 ± 0.02$</td>
<td>0.20</td>
<td>$-1.63 ± 0.02$</td>
</tr>
<tr>
<td>1f</td>
<td>0.24</td>
<td>$-1.42 ± 0.03$</td>
<td>0.27</td>
<td>$-1.3 ± 0.2$</td>
</tr>
</tbody>
</table>

Here $k(m_c)$ is the (pseudo-)first-order rate constant for hydrolysis in an m molal aqueous solution of solute c; $k(m_c = 0)$ is the rate constant in the absence of added cosolute, R is the gas constant, and T is the absolute temperature. $G(c)$ is the difference $[g_{oc} - g_{oc}]$ in interaction Gibbs energies between the cosolute c and the reactants x on one hand and the cosolute c and the activated complex $\cdot$ on the other hand. $m_c$ is the molal mass of water, N is the number of water molecules involved in the rate-determining step, and $\phi$ is the practical osmotic coefficient for the aqueous solution where the molality of added solute is $m_c$. In this study, N equals 2 (vide supra). Since the solutions are very dilute, $\phi$ can be taken as unity; $m_c$. 1 mol kg$^{-1}$ is the molality of the solute reference state. In short, $NM_c$ gives the change in water activity upon addition of $m_c$. As a function of molality of cosolute $m_c$, eq $\text{3,34,35}$

$$\ln[k(m_c)/k(m_c = 0)] = \frac{2}{RTm_c}G(c)m_c - NM_c\phi m_c$$

(3)

References:
(32) Hydrophobic interactions are rather dependent on size and shape of the hydrophobic (parts of) molecules involved; see e.g.: Southall, N. T.; Dill, K. A. J. Phys. Chem. B 2000, 104, 1326–1331. We therefore restricted our choice of alcohols for our mimicking solution to linear alcohols. The actual choice of linear alcohol is expected to be unimportant as all short-chain linear alcohols retard the hydrolysis reactions of activated amides in similar ways following an additivity scheme (see ref 35 and the following: Buurma, N. J.; Pastorello, L.; Blandamer, M. J.; Engberts, J. B. F. N. J. Am. Chem. Soc. 2003, 125, 11848–11853).
Nature of the Micellar Stern Region

FIGURE 2. Rate-retarding effects of 1-propanol (●) and TMAB (○) on the hydrolysis of probes 1a–f at 298.15 K as a function of Hammett substituent constants.

TABLE 4. Concentration Dependence (kg mol⁻¹) of Rate-Retarding Effects of 1-Propanol and TMAB on the Hydrolysis of Substituted 1-Benzoyl-1,2,4-triazoles 1a–f at 298.15 K

<table>
<thead>
<tr>
<th>Substituent</th>
<th>ln(k₉(m₉-propanol))/km₉(m₉ = 0)</th>
<th>ln(k₉(m₉-TMAB))/km₉(m₉ = 0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>-0.236 ± 0.005</td>
<td>-0.306 ± 0.015</td>
</tr>
<tr>
<td>1b</td>
<td>-0.232 ± 0.006</td>
<td>-0.240 ± 0.007</td>
</tr>
<tr>
<td>1c</td>
<td>-0.201 ± 0.005</td>
<td>-0.258 ± 0.006</td>
</tr>
<tr>
<td>1d</td>
<td>-0.151 ± 0.003</td>
<td>-0.259 ± 0.007</td>
</tr>
<tr>
<td>1e</td>
<td>-0.131 ± 0.003</td>
<td>-0.226 ± 0.002</td>
</tr>
<tr>
<td>1f</td>
<td>-0.058 ± 0.002</td>
<td>-0.240 ± 0.007</td>
</tr>
</tbody>
</table>

An alternative approach uses equations used in the study of 1:1 interactions in aqueous solutions. The rate-retarding effect in an aqueous solution containing 1-propanol is the derivative of the logarithm of the rate constant with respect to the concentration of 1-propanol.

\[
\frac{\partial \ln k_9(m_{propanol})}{\partial m_{propanol}} = k_{9,m_{propanol}} - k_{9,m_{mimic}}
\]

where \( m_{propanol} \) is the molality of 1-propanol and \( m_{mimic} \) is the molality of the mimetic surfactant. The rate-retarding effect caused by interactions with ionic headgroups (Figure 3).

Hydrolysis of a probe with a substituent with \( \sigma_p = 1.13 \) is expected to be solely retarded by ionic interactions. Because rate retardation by ionic interactions as modeled by TMAB is approximately constant for all hydrolytic probes, the horizontal dotted line at \( \ln[k_{9,CTAB}/k_9(m_c = 0)] = -1.0 \) indicates the constant "ionic contribution" to the rate-retarding effect for all hydrolytic probes. As the rate retardation (expressed in terms of logarithm of the relative rate retardation; vide supra) by ionic interactions is approximately -0.25 kg mol⁻¹ for TMAB, the micellar rate-retarding effect attributed to ionic interactions of -1.0 corresponds to a model solution of -1.0/0.25 mol kg⁻¹ = 4 mol kg⁻¹ in TMAB. The slope of the remainder of the rate-retarding effect, attributed to hydrophobic interactions, as a function of substituent parameter equals 1.07. As a slope of 0.17 is expected for a 1 mol kg⁻¹ solution, we estimate a model solution for the micellar Stern region to be approximately 1.07/0.17 = 6 mol kg⁻¹ in 1-propanol.

An alternative approach uses equations used in the study of 1:1 interactions in aqueous solutions. The rate-retarding effect in an aqueous solution containing 1-propanol and TMAB can be described as the sum of effects caused by added TMAB and 1-propanol:

\[
\frac{\partial \ln [k_9(m_{propanol})/k_9(m_{mimic})]}{\partial m_{propanol}} = k_{9,m_{propanol}} - k_{9,m_{mimic}}
\]

Equation 4 is more conveniently written in the form of eq 5:

\[
a_{x,1-propanol} m_{1-propanol} + a_{x,TMAB} m_{TMAB} = c_x
\]

Here, \( a_{x,1-propanol} \) is the derivative of the logarithm of the rate-retarding effect caused by 1-propanol with respect to its concentration, \( m_{1-propanol} \), and \( a_{x,TMAB} \) is the derivative of the logarithm of the rate-retarding effect caused by TMAB with respect to its concentration, \( m_{TMAB} \).
relative rate constant with respect to molality of 1-propanol, $a_{\text{TMBAM}}$ is the same derivative with respect to the molality of TMAB, and $c_x$ is the logarithm of the relative micellar rate constant. For a model solution consistently describing the micellar Stern region of the micelles formed by a certain surfactant, this equation should hold for all the hydrolytic probes in combination with this surfactant. Hence, for a given surfactant, there is a model solution of $m_{1\text{-propanol mol kg}^{-1}}$ in 1-propanol and $m_{\text{TMBAM mol kg}^{-1}}$ in TMAB in which the hydrolysis reactions of all hydrolytic probes 1a–f are retarded to the same extent as in the micellar Stern region. Hence, for every surfactant a set of linear equations is given by eq 5. In its extended form, these equations form the matrix given in eq 6:

$$
\begin{bmatrix}
    a_{\text{MeO,1-propanol}} & a_{\text{MeO,TMAB}} \\
    a_{\text{Me,1-propanol}} & a_{\text{Me,TMAB}} \\
    a_{\text{H,1-propanol}} & a_{\text{H,TMAB}} \\
    a_{\text{Cl,1-propanol}} & a_{\text{Cl,TMAB}} \\
    a_{\text{F,CO,1-propanol}} & a_{\text{F,CO,TMAB}} \\
    a_{\text{NO}_2,1-propanol} & a_{\text{NO}_2,TMAB}
\end{bmatrix}
\begin{bmatrix}
    m_{1\text{-propanol}} \\
    m_{\text{TMBAM}}
\end{bmatrix} =
\begin{bmatrix}
    c_{\text{MeO}} \\
    c_{\text{Me}} \\
    c_{\text{H}} \\
    c_{\text{Cl}} \\
    c_{\text{F,CO}} \\
    c_{\text{NO}_2}
\end{bmatrix}
$$

(6)

Overdetermined (not exact) matrix systems of the form in eq 6 can be solved using singular value decomposition.

The entries in vector $c_x$ and matrix $a_{x,c}$ are given in Tables 3 and 4, respectively. With application of the singular value decomposition method, a calculated model solution mimicking the micellar Stern region of a CTAB micelle is described in Table 5. The solution describes a "first-order solution" of eq 6, based entirely on extrapolated 1:1 interactions. This solution will be referred to as Soln.1.

The salt concentrations in Table 5 are lower than those in the concentrated salt solutions described in our previous paper where the salt was taken as the sole origin of rate retardation. Nevertheless, the salt concentrations match the calculated concentration ranges given in our previous report but now at the lower end of the calculated range. In fact, the value of 2.6 mol dm$^{-3}$ is in reasonable agreement with the concentrations of bromide anions (1.6 mol dm$^{-3}$) and ionic headgroups (2.0 mol dm$^{-3}$ assuming a counterion binding of 0.8) as determined by the Romsted group using their arenazidionium probe. Rate constants for hydrolysis of 1a–f and $E_T(30)$ value were determined for the solution mimicking CTAB made according to Table 5, i.e. in Soln.1(CTAB) (Table 6).

According to Table 6, rate constants for hydrolysis of individual probes in the model solution are only slightly higher than those in the CTAB Stern region. This discrepancy is attributed to the fact that hydrolysis data for 1a–f in binary aqueous solutions of TMAB or 1-propanol as determined at intermediate molalities have been extrapolated to higher molalities. In addition, the final solution is a ternary solution, introducing further deviations from the extrapolations for binary solutions. An encouraging observation is that the $E_T(30)$ value for the mimicking solution (55.8 kcal mol$^{-1}$) is in far better agreement with the value for CTAB micelles (53.5 kcal mol$^{-1}$) than the $E_T(30)$ values of the model solutions containing only TMAB.

Further, we calculated the expected micellar (CTAB and DTAB) rate constant of hydrolysis for 2. Using the molalities (and concentrations) determined here, together with the G(c) value of 1-propanol for hydrolysis of 2 determined previously and the dependence of the hydrolysis of 2 in aqueous solutions containing TMAB on molarity (Figure 2 in ref 1), the rate constant of the hydrolysis of 2 in the Stern region of CTAB micelles is expected to be $(1.4 \pm 0.4) \times 10^{-4}$ s$^{-1}$. Experimentally, a micellar rate constant of $(0.67 \pm 0.08) \times 10^{-4}$ s$^{-1}$ is observed. Similarly, the rate constant for the hydrolysis of 2 in DTAB micelles is expected to be $(1.1 \pm 0.3) \times 10^{-4}$ s$^{-1}$, in good agreement with the experimental micellar rate constant of $(1.26 \pm 0.05) \times 10^{-4}$ s$^{-1}$. In other words, the model predicts reasonably well reaction rates for reactions that were not used in the development of the model.

Using the results of the analysis, we describe the micellar binding and micellar inhibition in a single scheme (Scheme 2, different contributions not drawn to scale).

Both reactant (R) and activated complex (AC) bind to the micelle in the Stern region (Table 2). However, R binds much more strongly than AC, causing the rate retardation. We divide the Gibbs energy of binding of R to the micelle into a "dynamic" part, causing rate effects,
and a “passive” part, not causing rate effects (cf. a related division into passive and dynamic interactions in ref 38, for the present case the passive interactions correspond to $K^{AC}$. Using eq 6, the dynamic part has been divided into rate-retarding effects caused by interactions with ionic groups (as quantified by $a_{x,\text{TMAB}}$) and effects caused by interactions with hydrophobic groups (as quantified by $a_{x,1\text{-propanol}}$). For probes for which the dynamic part of the Gibbs energy of binding to the micelle is the same (i.e. probes with the same kinetic sensitivity toward hydrophobic and ionic interactions but for which the passive part is different), a linear relation between $pK_a$ and $pK^{AC}$ with a slope of 1 is expected. Indeed, such a linear relation is found for probes of which only the hydrophobicity is increased by elongating an alkylic chain remote from the reaction center.39 Similarly, the reason for the absence of a correlation between rate-retarding effects, micellar binding constants, and hydrophobicity of the surfactants constituting the micelle as found in this study stems from different and uncorrelated passive and dynamic contributions to the Gibbs energy of binding to the micelles.

The present analysis, separating the contributions of hydrophobic and ionic interactions, uses the differences in rate-retarding effects caused by hydrophobic interactions and ionic interactions. However, additional effects causing differences in rate-retarding effects have not been included in the present model. Three of these effects are readily identified, and their source, effect, and importance can be estimated.

First, different hydrolytic probes could bind in different zones of the micelle (or their distribution over different zones of the micelle could change31) and therefore experience different interactions. However, the kinetic probes used in this study are structurally similar and are all expected to reside in the micellar Stern region.11 Hence, any difference in rate effect caused by a difference in binding locations is expected to be of minimal importance.

Second, the electrostatic non neutrality of the micellar Stern region can (de)stabilize charges developing in the activated complex. In the present case, the partial negative charge on the AC will be stabilized by the effectively cationic Stern region. This effect will be modified by other factors (destabilizing the partial negative charge, e.g. (de)stabilization by substituent effects. Hence, different probes can be differently stabilized by the cationic nature of the micellar Stern region.

Third, the local pH in the Stern region may be different from the bulk pH. The local pH on the micellar surface can be calculated from the bulk pH and the micellar surface charge using the Poisson–Boltzmann equation.29 For a bulk pH of 4.0, the pH in the micellar Stern region of CTAB is calculated to be approximately 6.5. Experiments using 1e indicate that hydroxide-ion catalyzed hydrolysis contributes less than 5% to the rate constant of hydrolysis of 1e in the “second-order solution” (vide infra) at pH 6.5. This suggests that, for the system studied here, hydroxide-ion catalyzed hydrolysis as a result of the different pH is not an important factor.

Notwithstanding the fact that conclusions about the micellar binding sites can be drawn from the first-order solution, it would be useful to have a real solution accurately reproducing rate constants in the micellar Stern region. In the study of bimolecular reactions occurring in the Stern region, it is often especially difficult to determine independently binding constants for both reactants and the micellar rate constant.40–42 We therefore extended the model for CTAB to prepare a solution that includes the nonlinear rate-retarding effects at high molalities of TMAB and 1-propanol (vide supra). We determined these rate-retarding effects at high molality in much the same way as was used at low molality. Instead of using rate constants in water without added cosolute as reference points, rate constants in Soln.1, $k_x(m_{\text{TMAB}} = 4.85, m_{1\text{-propanol}} = 5.00)$, denoted as $k_x(Soln.1)$, were taken as reference points. Rate constants for hydrolysis of the hydrolytic probes in the presence of high molalities of TMAB and 1-propanol, $k_x(m_{\text{TMAB}}, m_{1\text{-propanol}})$, were determined in solutions where TMAB and 1-propanol molalities were around 4.85 and 5.00 mol kg$^{-1}$, respectively, i.e. around the molalities in Soln.1.

Plots of $\ln(k_x(m_{\text{TMAB}}, m_{1\text{-propanol}})/k_x(Soln.1))$ as a function of 1-propanol molality around the 1-propanol molality of Soln.1 and at a constant $m_{\text{TMAB}}$ of 4.85 mol kg$^{-1}$ are not linear (Figure 4).

Nevertheless, a linear fit, forced through the reference point provided by Soln.1, was used to obtain $\ln(k_x(m_{\text{TMAB}}, m_{1\text{-propanol}})/k_x(Soln.1))$ at $m_{1\text{-propanol}}$ (denoted $a_{x,1\text{-propanol}}$). For the dependence on $m_{\text{TMAB}}$, only one additional data point (for every probe) was determined as an indication of $\ln(k_x(m_{\text{TMAB}}, 5.00)/k_x(Soln.1))$ at $m_{\text{TMAB}}$ (denoted $a_{x,\text{TMAB}}$). The calculated slopes are given in Table 7.

An improved estimate of the molalities for a model solution accurately reproducing micellar rate constants can be determined starting from the first-order solution. Equation 6 with $c_x = \ln(k_x(m_{\text{TMAB}}, k_x(Soln.1))$ (the residual of the first-order model solution) and with $a_{x,1\text{-propanol}}$ and $a_{x,\text{TMAB}}$ set to $a_{x,1\text{-propanol}}$ and $a_{x,\text{TMAB}}$ (Table 7),

\begin{align*}
\ln(k_x(m_{\text{TMAB}}, m_{1\text{-propanol}})/k_x(Soln.1)) = a_{x,1\text{-propanol}} \cdot m_{1\text{-propanol}} + a_{x,\text{TMAB}} \cdot m_{\text{TMAB}}
\end{align*}

FIGURE 4. Representative examples of the rate-retarding effect of (additional) added 1-propanol on the hydrolysis of 1a (C), 1b (a), 1d (●), and 1f (♦) at 298.15 K at a constant TMAB molality $m_{\text{TMAB}}$ of 4.85 mol kg$^{-1}$, using Soln.1 as reference.

(42) It is expected that the micellar rate constants as reported in refs 40 and 41 will be reasonably well reproduced by the model solutions reported here. This is expected because water concentrations are less than 30 M in all the presented model solutions.

respective yields a correction term for the “first-order solution” equal to \( +2.7 \pm 0.9 \text{ mol kg}^{-1} \) for 1-propanol and \( +0.8 \pm 0.4 \text{ mol kg}^{-1} \) for TMAB. Therefore the “second-order solution” (Soln.2) should contain 7.7 \pm 0.9 \text{ mol kg}^{-1} 1-propanol and 5.7 \pm 0.4 \text{ mol kg}^{-1} TMAB. We tested this second-order solution. The rate constant for hydrolysis of 1e, which is most sensitive to ionic interactions, equals \( 7.6 \times 10^{-4} \text{ s}^{-1} \), in good agreement with the micellar rate constant of \( (7.0 \pm 0.1) \times 10^{-4} \text{ s}^{-1} \). The \( E_r(30) \) value, which is most sensitive to hydrophobic interactions, equals 54.4 \pm 0.2 \text{ kcal mol}^{-1} \), in reasonable agreement with the micellar value\(^a\) of 53.5 \text{ kcal mol}^{-1} (90% of the decrease in excitation energy accounted for)\(^b\). In addition, the rate constant for hydrolysis of 2 in Soln.2 is \( (9.5 \pm 0.5) \times 10^{-5} \text{ s}^{-1} \), in reasonable agreement with the micellar rate constant of \( (6.7 \pm 0.8) \times 10^{-5} \text{ s}^{-1} \) (88% of the increase in Gibbs energy of activation accounted for). Therefore, reasonable estimates of micellar rate constants and even micropolarity, as determined using the \( E_r(30) \) probe, can be obtained using the present model solution for CTAB. Furthermore, the results obtained for 2 and the \( E_r(30) \) probe (both were not used in the optimization of our model) suggest that this can also be done for reactions and properties that were not included in the construction of the model. Hence, the present model is the first to be able to reproduce a diverse range of medium-controlled properties of the micellar Stern region and it indicates that other effects that were not included in the analysis (vide supra) play only a minor role.

The present model is not limited to alkyltrimethylammonium bromide surfactants. Comparable model solutions can also be determined for other surfactants, both ionic- and vesicle-forming, provided the salt mimicking the micellar headgroups is appropriate. Availability of solutions mimicking the micellar Stern region is especially helpful for determining factors underlying either micellar catalysis or inhibition of bimolecular (or higher molecularity) reactions. Despite the emphasis on reaction kinetics in this study, virtually any property of the micellar Stern region can be used in similar analyses.

### Conclusions

The failure of concentrated salt solutions to reproduce polarity-related properties of the micellar Stern region\(^1\) indicated the necessity of expanding our previous model mimicking the Stern region in such a way that rate-retarding hydrophobic interactions are correctly taken into account. For DTAB and CTAB, this has been accomplished by modeling the micellar Stern region using an aqueous solution containing both 1-propanol, mimicking hydrophobic surfactant tails, and TMAB, mimicking ionic surfactant headgroups. The molalities of TMAB and 1-propanol in these solutions can be determined graphically and mathematically, using singular value decomposition. We distinguish two “types” of model solutions, viz. first-order and second-order solutions. First-order solutions are determined from the rate-retarding effects of 1-propanol and TMAB at intermediate molalities and indicate the relative importance of ionic and hydrophobic groups in the micellar Stern region. Second-order solutions can be derived from first-order solutions and take into account the nonlinear rate retardations at high molalities of cosolutes. Second-order solutions can be used to obtain estimates of micellar rate constants for reactions of which the micellar rate constants cannot be determined directly. The present approach can be used for both micellar and vesicular systems and probably has an even wider applicability.

### Experimental Section

Substituted 1-benzoyl-1,2,4-triazoles (1a–f) and 1-benzoyl-3-phenyl-1,2,4-triazole (2) were synthesized according to literature procedures.\(^{44} \) The \( E_r(30) \) probe was kindly provided by Prof. Dr. Chr. Reichardt. Micellar solutions were \( 1 \times 10^{-4} \text{ mol dm}^{-3} \) in HCl, and model compound solutions were acidified to pH 4 to achieve conditions for pH-independent hydrolysis. All solutions were made in water that was distilled twice in an all-quartz apparatus. Surfactants and salts were dried before use. If solutions were made volumetrically, the mass of all components of the solutions was determined to know both solute and solvent concentration. If model solutions were made by weight, the density was determined. Reactions were followed at 260, 262, 252, 262, 253, and 262 nm for 1–f, respectively, and at 273 nm for 2, at 298.15 \pm 0.2 \text{ K} \) for at least 6 half-lives. Good to excellent pseudo-first-order kinetics were obtained, the error in the rate constants being 2% or less for the micellar solutions and the dilute solutions but up to 10% for the concentrated solutions.

The probes were injected as \( 6 \mu \text{L} \) of a stock solution of 1a–f or 2–5 \((\mu \text{L}) \) of a stock solution of 2 in cyano methane into a 1 cm quartz cuvette of ca. 2.5 mL yielding a total probe concentration during the reaction of ca. \( 10^{-5} \text{ mol dm}^{-3} \). These concentrations were chosen to have absorbance changes not larger than 0.6.

The measurements involving the \( E_r(30) \) probe were performed at pH 11. The \( E_r(30) \) probe was injected as \( < 6 \mu \text{L} \) of a stock solution of the solvatochromic probe in EtOH.

The singular value decomposition method was used as implemented in Mathcad 2001 Professional by Mathsoft Inc.

### Acknowledgment

Marie Jietta den Otter is gratefully acknowledged for her contribution to this work.

---