INHIBITON EFFECT OF CATIONIC MICELLES ON THE BASIC HYDROLYSIS OF AROMATIC ESTERS

S. VERA and E. RODENAS[*]

Physical Chemistry Department, University of Alcalá
de Henares, Alcalá de Henares, (Madrid), SPAIN

Abstract.- The basic hydrolysis of 4-acetoxybenzoic acid and 2-naphtyl-
acetate have been studied in cationic micelles of N-cetyl-N,N,N-tri-
methylammonium bromide and hydroxide and the results compared with the
ones obtained for the basic hydrolysis of acetylsalicylic acid and
3-acetoxy-2-naphtoic acid. The results can be explained with the pseudo-
phase kinetic model and the determined second order rate constants in
micelles are also smaller than the second order rate constants in water.

INTRODUCTION

During the past two decades there has been considerable interest in reactions which can be
carried out at interfaces. One important aspect is the catalysis or inhibition reactions by sub-
microscopic entities such as micelles,[1-5] that now are considered as models for enzymes action
because they are similar in size and shape, both have polar surfaces and hydrophobic interiors,
and recently a number of micellar induced steroselective and regioselective reactions have been
studied.[6-11] The effect of ionic micelles on the rates of bimolecular reactions is due to in-
creased concentration of the two reactants with in the smmall volume of the micellar Stern layer.[1]
This effect is specially important in reactions that imply the attack of an organic substrate by
an ionic reactive. Simple electrostatic considerations predict that the cationic micelles will
enhance reactions rates by negative ions while anionic micelles catalyze reactions involving
positive ions.[1]

Generally, rate constants in micelles are similar to those in water and the differences are
due to both properties of micelles as kinetic solvent and the different location of the two
reactants in the micelles. However, there are some exceptions to this generalization where the
rate constants in micellar solutions are either larger [12,13] or smaller [14-16] than the rate
constants in water, and in earlier studies it has been already reported that cationic micelles
of N-cetyl-N,N,N-trimethylammonium bromide and hydroxide (CTABr and CTAOH respectively), inhibit
the basic hydrolysis of two aromatic esters as acetylsalicylic acid and 3-acetoxy-2-naphtoic
acid,[14-16] which have a negative charge due to dissociation of the carbolylic acid group of the
molecule.

In this paper, we have studied the basic hydrolysis of the 4-acetoxybenzoic acid and the 2-
naphtylacetate in cationic micelles of CTABr and CTAOH, and the results have been compared with
the obtained for this reaction with acetylsalicylic acid and 3-acetoxy-2-naphtoic acid. Our aim
has been examine the influence of the dissociated carboxylic acid group upon the basic reaction
of these aromatic esters.

DISCUSSION

The second-order rate constant, k_w, for the aqueous basic hydrolysis of 4-acetoxybenzoic acid
is 88.8 $1.mol^{-1}min^{-1}$ and 97.1 $1.mol^{-1}min^{-1}$ for the 2-naphtylacetate.

Experimental pseudo-first order rate constants for the reaction in micellar solution of CTABr and CTAOH, k_ψ, are represented by dots in Figure 1 and Figure 2 for the substrate 4-acetoxy-benzoic acid and in Figure 3 and Figure 4 for the 2-naphtylacetate. For unreactive counterion surfactants, as CTABr, the k_ψ variation with surfactant concentration follows a typical pattern, pseudo-first order rate constants goes through maxima with increasing surfactant concentration at constant hydroxide ion concentration (Fig.1 and Fig.3). In the case of reactive counterion surfactant, as CTAOH, pseudo-first order rate constants increase as increasing CTAOH concentration (Fig.2 and Fig.4).
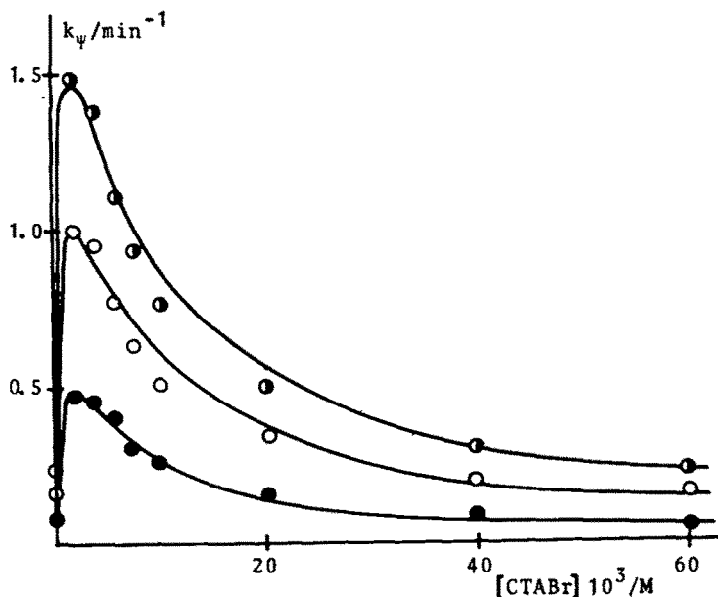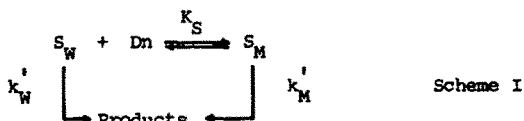

Fig.1 .- Variation of the pseudo-first order rate constant k_ψ with CTABr concentration for 4-ace-toxybenzoic acid:●[NaOH]=0.001 M,○[NaOH]=0.002 M, ◐[NaOH]=0.003 M.Lines are predicted values.

The results obtained for the basic hydrolysis of both esters in presence of CTABr can be explained by means of the pseudophase kinetic model proposed by Menger[19] and developed by Bunton[20] and Romsted.[21,22] This model considers the total volume of micelles as a separate phase uniformly distributed in the aqueous phase, the reaction ocurring in both phases according to Scheme I, where the suscripts M and W denote the micellar and aqueous phases respectively, S is the substrate, Dn the micellized surfactant whose concentration is given by $[Dn]=[D]-cmc$, cmc is the critical micelle concentration, K_S the binding constant of the substrate to the micelle

$$S_W + Dn \xrightleftharpoons[\ ]{K_S} S_M$$

$$k'_W \downarrow \qquad \qquad \downarrow k'_M \qquad \qquad \text{Scheme I}$$

$$\longrightarrow \text{Products} \longleftarrow$$

written in terms of micellized surfactant:

$$K_S = \frac{[S_M]}{[S_W][Dn]} \qquad [1]$$

k'_W and k'_M are the pseudo-first order rate constants in aqueous and micellar pseudophases respectively, given by:

$$k'_W = k_W [OH^-_W] \qquad [2]$$

$$k'_M = k_M [OH^-_M]/[Dn] \qquad [3]$$

where k_M is written in terms of the mole ratio of micellar OH^- bound to the micellar head groups.

For reactions involving ions Romsted[21,22] proposed a theoretical method assuming that ions bind to micelles according to the exchange model developed for ion-exchange resins and considering that the fraction of micellar head groups neutralized, β, can be taken as a constant when one of the ions in solution binds very strongly to micelle.[21,22] For OH^- reactive ion and Br^- as micelle counterion the ion-exchange equilibrium can be expressed by:
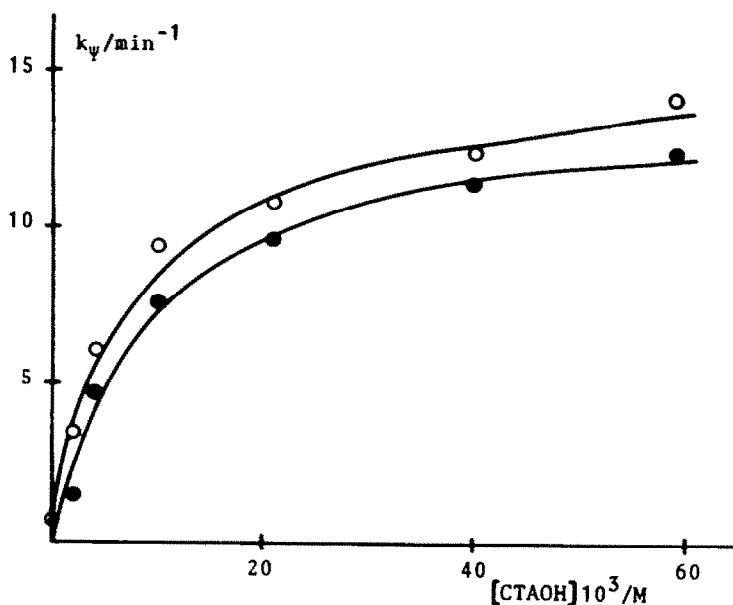
$$OH^-_M + Br^-_W \rightleftharpoons OH^-_W + Br^-_M$$

Fig.2.- Variation of the pseudo-first order rate
constant k_ψ with CTAOH concentration for 4-ace-
toxybenzoic acid: ● only CTAOH,○[NaOH]= 0.01 M.
Lines are predicted values.

with an equilibrium constant:

$$K_{Br}^{OH} = \frac{[OH_M^-] [Br_W^-]}{[OH_W^-] [Br_M^-]} \qquad [4]$$

Setting $m_{OH} = [OH_M^-]/[Dn]$, $m_{Br} = [Br_M^-]/[Dn]$ and $\beta = m_{OH} + m_{Br}$, according to Scheme I and equations
[1]-[4] the pseudo-first order rate constant can be easily derived as:

$$k_\psi = \frac{k_W [OH_T^-] + (k_M K_S - k_W) m_{OH} [Dn]}{1 + K_S [Dn]} \qquad [5]$$

where m_{OH} can be expressed by:

$$m_{OH}^2 + m_{OH}\left[\frac{[OH_T^-] + K_{Br}^{OH} [Br_T^-]}{(K_{Br}^{OH}-1)[Dn]} - \beta\right] - \frac{\beta [OH_T^-]}{(K_{Br}^{OH}-1)[Dn]} = 0 \qquad [6]$$

where $[OH_T^-] = [OH_W^-] + [OH_M^-]$ and $[Br_T^-] = [Br_W^-] + [Br_M^-]$.

According to Romsted's ion-exchange model it is possible to explain the k_ψ-[CTABr] profiles
because at small surfactant concentration the relative concentrations of substrate and ionic
reactive in the micellar Stern layer increase rapidly with the amount of surfactant accelerating
the reaction and this effect can account for the ascending branch of the curve. Once all the
substrate is in the micellar pseudophase, an increase in the surfactant concentration of the
unreactive counterions, Br⁻, that displaces the micellar bound OH⁻ ions of the proximity of the
bound substrate. This could account for the descending branch of the experimental curve at high
surfactant concentration.

The experimental rate constants can be adapted to equations [1]-[6] using a computer program
which allowed us to simulate the variation of k_ψ with surfactant and reactive ion concentration
at different values of parameters in these equations.[23] The value of cmc affects very little the
value of k_ψ and although it decreases slightly with electrolite addition, we can safety use the
value found in the literature for aqueous solutions, cmc(CTABr)=9x10⁻⁴ M.[24] The parameter β can
be taken as a constant in this cationic surfactant with Br⁻ as counterions, with a value of 0.8
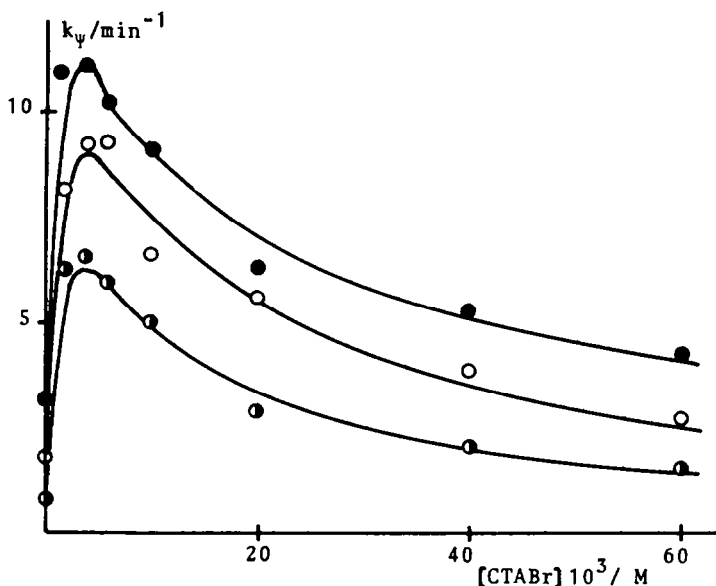.[21-23] The kinetic constant k_W is the value obtained for the aqueous basic hydrolysis. The other

Fig.3.~ Variation of the pseudo-first order rate
constant k_ψ with CTABr concentration for 2-naphtyl-
acetate:◑ [NaOH]=0.01 M,O[NaOH]=0.02 M,●[NaOH]=0.03 M.
Lines are predicted values.

parameters k_M, K_S and K_{Br}^{OH} can be used as adjustable parameters. Table I and Table II give the values of parameters that best fit the experimental results for the basic hydrolysis of 4-acetoxybenzoic acid and 2-naphtylacetate respectively, and the solid lines on Fig.1 and Fig.3 show the values of k_ψ so calculated.

Table I. Parameters that best fit the kinetic results for 4-acetoxybenzoic acid in CTABr

$[OH_T^-]$/ M	k_M /min^{-1}	K_S/ M^{-1}	K_{Br}^{OH}	β
1×10^{-3}	17.0	250	16	0.8
2×10^{-3}	21.0	300	16	0.8
3×10^{-3}	21.8	320	16	0.8

Table II. Parameters that best fit the kinetic results for 2-naphtylacetate in CTABr

$[OH_T^-]$/ M	k_M /min^{-1}	K_S/ M^{-1}	K_{Br}^{OH}	β
1×10^{-2}	32.0	680	8	0.8
2×10^{-2}	32.0	680	8	0.8
3×10^{-2}	32.5	680	8	0.8

For reactive counterion micelles as CTAOH, the distribution of OH$^-$ between aqueous and micellar pseudophases can be fitted to a mass-action model [25] as:
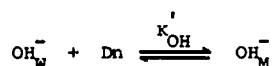
$$OH_W^- \ + \ Dn \ \underset{}{\overset{K_{OH}'}{\rightleftharpoons}} \ OH_M^-$$

where

$$K_{OH}' = \frac{[OH_M^-]}{[OH_W^-]\,([Dn]-[OH_M^-]\,)} \qquad [7]$$

which reduces to

$$K_{OH}'\,[OH_M^-]^2 - (K_{OH}'[Dn]+K_{OH}'[OH_T^-]+1)[OH_M^-] +K_{OH}'[Dn]\,[OH_T^-] =0 \qquad [8]$$

Equation [7] predicts that β increases with surfactant concentration according to $\beta=[OH_M^-]/[Dn]$.

The experimental results in CTAOH can be fitted to equations [5] and [8] using cmc(CTAOH)=8.4×10^{-4} M [25] and determining K_S,K_{OH}' and k_M by simulation techniques. For reaction with 4-acetoxybenzoic acid the values of parameters that best fit the experimental results are k_M= 16.3 min^{-1}, K_S= 380 M^{-1} and K_{OH}'= 230 M^{-1} and for reaction with 2-naphtylacetate are
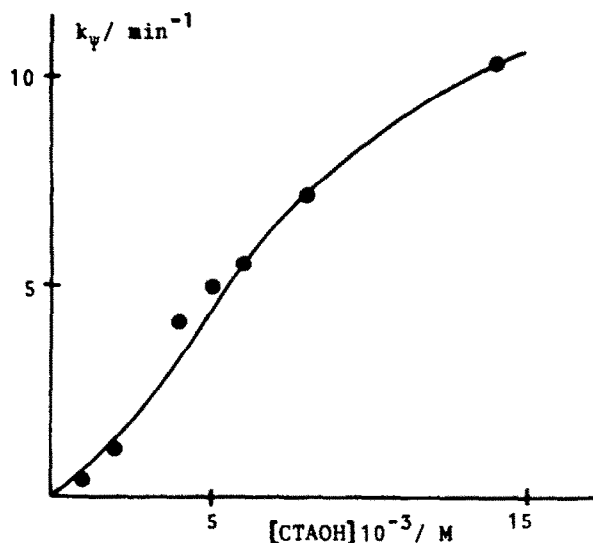
Fig.4.- Variation of the pseudo-first order rate constant k_ψ with CTAOH concentration for 2-naphtylacetate:● only CTAOH.Line is predicted value.

k_M=31.0 min^{-1}, K_S=800 M^{-1} and K'_{OH}=60 M^{-1}. Solid lines in Fig.2 and Fig.4 represent the calculated values of k_ψ with these parameters.

Rate constants in micellar pseudo-phase, k_M, cannot be compared directly with the second-order rate constant in water, k_W. The comparison can be made considering that the volume of Stern layer of micelles, 0.14 l.mol^{-1}, is the volume element of reaction in the micellar pseudophase [26], so that the second-order rate constant in the micellar pseudophase, k_2^m, is:

$$k_2^m = k_M \ 0.14$$

In this form, the second-order rate constant in micellar pseudophase is thirty times smaller than the second-order rate constant in water for reaction of 4-acetoxybenzoic acid and twenty times smaller for the reaction of 2-naphtyl acetate.

Table III shows the values of parameters that explain the experimental results for the basic hydrolysis of the esters studied, 4-acetoxybenzoic acid and 2-naphtylacetate, as well as those of the already reported acetylsalicylic acid and 3-acetoxy-2-naphtoic acid.[14-16]

Table III. Parameters that best fit the kinetic results for the basic hydrolysis of various aromatic esters in cationic micelles.

Substrates	k_W/k_2^m	K_S/ M^{-1}	K'_{OH}/M^{-1}	K_{Br}^{OH}
Acetylsalicylic acid[a]	≃ 80	177 (CTABr) 350 (CTAOH)	380	2
4-acetoxybenzoic acid	≃ 30	290 (CTABr) 380 (CTAOH)	230	16
3-acetoxy-2-naphtoic acid[b]	≃ 100	500 (CTABr) 800 (CTAOH)	380	5
2-naphtylacetate	≃ 20	680 (CTABr) 800 (CTAOH)	60	8

a) Ref.14-15, b) Ref.16

From these parameters values it can be deduced that the values of binding constant of substrate to micelle, K_S, are higher for the more hydrophobic esters as it was expected.[1,4,22] The value of K_S for the uncharged substrate, 2-naphtylacetate, is higher than values of this constant for charged substrates. This effect can be explained considering the different interaction and localization of substrates in the micelles, thus it could be established that solubilization of charged esters occurs next to polar surface of CTAX micelles and for this reason the binding constants are smaller, this is in agreement with other observations in the literature.[27,28] It is interesting to point out that K_S values in CTAOH are higher than ones in CTABr, this effect can be explained considering that neutralized micelar surface in CTAOH is smaller that in CTABr because of the different ion hydrophobicity [3,21,22] and that electrostatic interactions micelle-

substrate are important in the binding to micelle.

Values of K'_{OH} and K^{OH}_{Br} are different to other values given in the literature [22,23,29-31] and it can be related with the different interaction of substrates to micellar surface that affects the ion-binding and the ion-exchange equilibria. These cationic micelles of CTAX ($X=Br^-,OH^-$) inhibit the basic hydrolysis of all the studied substrates according to the ratio k_w/k^m_2 in Table III. That means that binding of substrates to cationic micelles stabilizes the ground state much more than the transition state, basically if the carboxylic acid group is present in position orto.

It is interesting to remark that the kinetic model developed for the basic hydrolysis of acetylsalicylic acid and 3-acetoxy-2-naphtoic acid that permits to estimate the variation of β with surfactant concentration as a function of independent distribution equilibrium constants of the ions in solution,[16] cannot explained the experimental results for the basic hydrolysis of 4-acetoxybenzoic acid and 2-naphtylacetate. It is possible to consider that although the measure- ments by ligh scattering suggest that β increases on addition of counterions in solution,[32,33] this model predicts a too high variation of β to explain all experimental results.

We can conclude that in the interaction of charged substrates to ionic micelles are important the electrostatic forces as well as hydrophobic forces that change the surface polarity of micelle and thus affect the ion-equilibria and the binding-equilibria of substrates which affect strongly the rate of reactions.

EXPERIMENTAL SECTION

The substrates 4-acetoxybenzoic acid and 2-naphtylacetate were prepared from 4-hydroxybenzoic acid and 2-naphtol respectively, with acetic anhydride at room temperature and the products recrystallized from EtOH according to the general procedure (Ref.17). The surfactant CTABr (Merck) was recrystallized from MeOH/Et$_2$O mixture, and the surfactant CTAOH was prepared by ion exchange from CTABr (Ref.18) with an anionic resin Amberlita 21K. This surfactant was prepared and kept under N_2 and it was only used the following day after preparation. The absence of Br^- in CTAOH was tested with silver ion.

All the reactions were run at 25±0.1°C in thermostated cuvettes of an Spectronic 2000 Bausch&Lomb spectrophotometer. Both substrates were complrtely dissociated under our experimental conditions and the reactions were followed at the wavelengths corresponding to the respective products of the reaction: 275 nm for the 4-hydroxibenzoic acid in absence and in presence of micelles and 340 nm for aqueous reaction and 351 nm for micellar reaction of 2-naphtol.

To the mixture of CTAX ($X=Br^-$, OH^-) and NaOH at a given concentrations in the thermostated cuvettes 0.1 ml of 4-acetoxybenzoic acid (0.0003 M) or 2-naphtylacetate (0.003 M) stock solutions in acetonitrile was added so that the amount of CH_3CN in the reaction mixture was 3%. The con- centrations used were: [NaOH]=0.001 to 0.03 M; [CTAX]=0.001 to 0.06 M and 10^{-5} M or 10^{-4} M for 4-acetoxybenzoic acid or 2-naphtylacetate respectively. The hydroxide ion concentration was always in larger excess over both substrates. Values of pseudo-first order rate constants were obtained by least-squares fit with correlation coefficients greater than 0.999.

REFERENCES

1.- Fendler,J.H.;Fendler,E.J. "Catalysis in M*cellar and Macromolecular Systems",Academic Press, New York, 1975.
2.- "Reactions Kinetics in Micelles",Cordes,E.H.,Ed.;Plenum Press,New York,1973
3.- Fendler,J.H. "Membrane Mimetic Chemistry", Wiley-Interscience,New York, 1982
4.- "Micellization, Solubilization and Microemulsions", Mittal,K.,Ed.;Plenum Press,New York, 1982
5.- "Solution Behavior of Surfactants:Theoretical and Applied Aspects", Mittal,K., Fendler,E.J., Ed.;Plenum Press,New York, 1982
6.- Kunitake,T.;Okahata,Y. J.Am.Chem.Soc., 1976,98,7794; 1976,98,7800
7.- Okahata,Y.;Ando,R.;Kunitake,T. J.Am.Chem.Soc., 1977,99,3067
8.- Ihara,Y.;Nango,M.;Kimura,Y.;Kuroki,N. J.Am.Chem.Soc., 1983,105,1252
9.- Moss,R.;Lee,Y.;Alwis,K. J.Am.Chem.Soc., 1980,102,6648
10.- Ihara,Y.;Nango,M.;Kuroki,N. J.Chem.Soc.Chem.Commun.,1981,393
11.- Ihara,Y.;Hosako,R.;Nango,M.;Kuroki,N. J.Org.Chem., 1980,45,5011
12.- Bunton,C.A.;Rodenas,E.;Moffatt,J.R. J.Am.Chem.Soc., 1982,104,2653
13.- Rodenas,E. An.Quim., 1983,79,638
14.- Vera,S.;Rodenas,E.;Ortega,F.;Otero,C. J.Chim.Phys., 1983,80,543
15.- Vera,S.;Rodenas,E. An.Real Acad.Farm., 1984,50,73
16.- Rodenas.E.;Vera.S. J.Phys.Chem., 1984,89,513
17.- Marshall,E.;Kuck,J.;Elderfields,R. J.Org.Chem., 1942,7,450
18.- Ortega,F. personal communication
19.- Menger,F.;Portnoy,C. J.Am.Chem.Soc., 1967,89,4698
20.- Bunton,C.A. Catal.Rev.-Sci.Eng., 1979,20,1
21.- Romsted,L.S. In reference 4 vol.2,p.509
22.- Romsted,L.S. Symposium on Surfactants in Solution, Lund, Sweden, 1982
23.- Al-Lohedan,H.;Bunton,C.A.;Romsted,L.S. J.Phys.Chem., 1981,85,2123

24.- Mukerjee,P,;Mysels,K. "Critical Micelle Concentration of Aqueous Surfactant Systems",NSRDS-NBS-36,Washington D.C. 20402,1971

25.- Bunton,C.A.;Gan,L.;Romsted,L.S.;Savelli,G. J.Phys.Chem., 1981,85,4118

26.- Bunton,C.A.;Carrasco,N.;Huang,K.;Paik,C.;Romsted,L.S. J.Am.Chem.Soc., 1978,100,5420

27.- Eriksson,J.;Gillberg,G. Acta Chem.Scand., 1966,20,2019

28.- Ulmius,J.;Lindman,B.;Lindblom,G.;Drakemberg,T. J.Colloid Interface Sci., 1978,65,88

29.- Bunton,C.A.;Romsted,L.S. in reference 5, vol.2,p.975

30.- Al-Lohedan,H.;Bunton,C.A. J.Org.Chem. 1982,47,1160

31.- Bartet,D.;Gamboa,C.;Sepulveda,L. J.Phys.Chem., 1980,84,272

32.- Rhode,A.;Sackmann,E. J.Colloid Interface Sci., 1979,70,494

33.- Rhode,A.;Sackmann,E. J.Colloid Interface Sci., 1980,84,1598