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Studies on the Use of Surfactants in Aqueous Diels-Alder Reactions

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Abstract: The effects of added surfactants on the aqueous Diels-Alder reaction between cyclopentadiene and a range of acrylate esters have been studied. The surfactants were used at their critical micellar concentrations, and the pH of the aqueous solutions was varied to determine the optimum conditions for the formation of the *endo* cycloadduct.

The use of micellar solutions as reaction media offers some fascinating possibilities for reaction control by virtue of the special properties which surfactants can confer such as: substrate solubilisations; the concentration effect; the cage effect; the preorientation effect; the effect of microviscosity, and polarity and charge effects.[1] The reported applications of such media include photochemical reactions,[2] and nucleophilic substitution reactions[3].

Within this context, we now wish to describe the results of a preliminary model study on the preorientation and solubilisation effects of surfactants at their critical micellar concentrations (**cmc**) on the Diels-Alder reaction between cyclopentadiene and acrylate esters. While the first Diels-Alder reaction in water alone as a solvent was reported by Diels and Alder themselves[4], subsequent work by Woodward and Bauer,[5] and in particular by Breslow[6] has clearly demonstrated that rate enhancements and higher *endo* selectivities can be achieved in this solvent. However, the effect of added surfactants has received little attention. Thus, from a study of the reaction between cyclopentadiene and methyl acrylate,[7] in the presence of either sodium dodecyl sulphate (SDS) and cetyltrimethylammonium bromide (CTAB) solutions (both at 0.02 M), in which *endo/exo* (*N/X*) ratios of five to nine were obtained, Breslow concluded that the detergent had little effect (compared to water) on the product ratios, and that the use of SDS gave rise to only a slight rate enhancement. In a subsequent study by Sauer[8], using methyl and *n*-butyl acrylate, large rate enhancements were claimed when comparing the use of an SDS solution to dioxan and *N/X* ratios varying in the range six to nine were reported for *n*-butyl acrylate in surfactant solutions. However, the selectivities in water were not reported and unfortunately, the concentration of surfactant used in this study was also not indicated.

As part of our research programme investigating the effect of surfactant solutions on yield and product selectivity, a range of acrylates from methyl to nonyl were accordingly prepared. The results[9] for the series of experiments between the acrylate esters and cyclopentadiene, in water and in the presence of the cationic surfactant CTAB and the anionic surfactant SDS, both at their critical micellar concentrations, are set out in Table 1 below, and reveal several features of interest.

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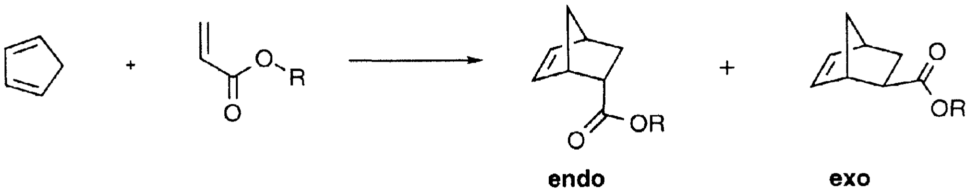

Entry	R	Solvent	Surfactant[b]	Time/h	Yield	N/X
1	methyl	water	-	4	5	9.3
2	methyl	water	CTAB	4	21	18.0
3	methyl	methanol	-	4	11	8.8
4	methyl	diethyl ether	-	4	0	-
5	methyl	water	-	72	89	6.6
6	methyl	water	CTAB	72	80	6.5
7	methyl	diethyl ether	-	72	48	3.1
8	ethyl	water	-	4	65	6.0
9	ethyl	water	CTAB	4	92	7.2
10	ethyl	diethyl ether	-	4	3	6.0
11	ethyl	water	-	72	79	4.8
12	ethyl	water	CTAB	72	92	5.5
13	ethyl	diethyl ether	-	72	7	3.2
14	pentyl	water	-	4	42	1.6
15	pentyl	water	CTAB	4	68	1.7
16	pentyl	diethyl ether	-	4	0	-
17	heptyl	water	-	4	18	1.7
18	heptyl	water	CTAB	4	37	1.7
19	nonyl	water		4	35	1.8
20	nonyl	water	CTAB	4	29	1.2
21	nonyl	water	-	72	80	1.7
22	nonyl	water	CTAB	72	70	1.7
23	nonyl	water[c]	-	72	71	2.4
24	nonyl	water[c]	CTAB	72	38	2.0
25	nonyl	water[c]	SDS	72	79	2.1

a) Reactions were carried out at ambient temperature. 3.80 mmol of cyclopentadiene was reacted with 1.90 mmol of acrylate in 25ml of solution. b) CTAB was used at its **cmc** of 0.026 mM, SDS was used at its **cmc** of 8.3 mM. c) 38 mmol of cyclopentadiene was reacted with 19 mmol of nonyl acrylate in 25 ml of solution.

Table 1[a]

Thus, when using methyl acrylate (entries **1-4**) the selectivities in water agreed exactly with Breslow's report. However, in sharp contrast, the use of CTAB led to much higher *endo*/*exo* (*N/X*) ratios of 18 when compared to his value of 8.8. Since the critical micellar concentration (**cmc**) of CTAB is 0.026 mM and that of SDS is 8.3 mM, the aqueous solutions used in Breslows' work contained detergent at 770 and 2.4 times the **cmc** respectively. This suggests that careful selection of the surfactant concentration can have a dramatic effect on product selectivity. The different selectivities observed may well be related to the shape of the micellar aggregate which is often spherical when concentrations close to the **cmc** are chosen, but is known to become ellipsoidal or rod shape at higher concentrations.[1]

At longer reaction times (entries **5-7**) the *N/X* values decreased as expected, since in such Diels-Alder reactions, the retro reaction also occurs readily and the more stable thermodynamic *exo* product can predominate. In addition, yields and selectivities were very similar in micellar and non-micellar media. Overall, these initial experiments clearly demonstrated that the effect of the surfactant CTAB is pronounced in terms of higher yields and higher selectivities over the shorter reaction time scale.

We expected a similar trend with ethyl acrylate (entries **8-13**), but found that the *N/X* ratio when using water and surfactant solutions were in the same region, however, the amount of isolated product was significantly higher with CTAB than for water alone, and these yields were substantially higher than with organic media. Again for longer reaction times lower N/X ratios were observed as the quantity of the thermodynamic product increased (entries **11-13**).

When the chain length was further increased to pentyl acrylate (entries **14-16**), and heptyl acrylate (entries **17-18**) again the *N/X* ratios for both water and surfactant solutions were similar but had dropped to around 1.6, reflecting the effect of the longer alkyl chain on the preference for the formation of the thermodynamic product with the ester and alkyl chain in a pseudo-equatorial position. As for the shorter chain esters the yields in surfactant media were higher.

The series of experiments with nonyl acrylates (entries **19-25**) provided additional highlights. In this case, there is either no or only a marginal increase in yield in surfactant media. A possible explanation may be the tendency for nonyl acrylate to self aggregate and indeed initial investigations suggest that a non-micellar aggregate is formed.[10] When performing the reaction at ten times the concentration in aqueous solutions slightly higher *N/X* selectivities were observed. It is therefore apparent that there is an optimum chain length for the substrate to participate effectively in micellar catalysis.

At this stage of our study we reasoned that the pH of the reaction medium could play a vital role in such reactions and perhaps explain the differing selectivities observed in previous studies by different groups. To our surprise, little mention has been made of this parameter in the literature. Herein, the hitherto unrecognised influence of the pH of the aqueous phase on the reactions are reported, both in water and surfactant media. The effect of the pH on the reaction between nonyl acrylate and cyclopentadiene in water is summarised in Figure 1 below.[11]

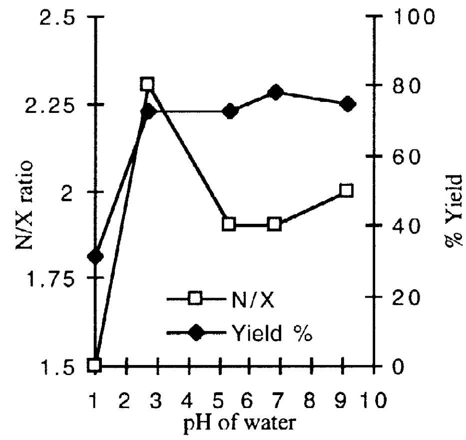

Figure 1

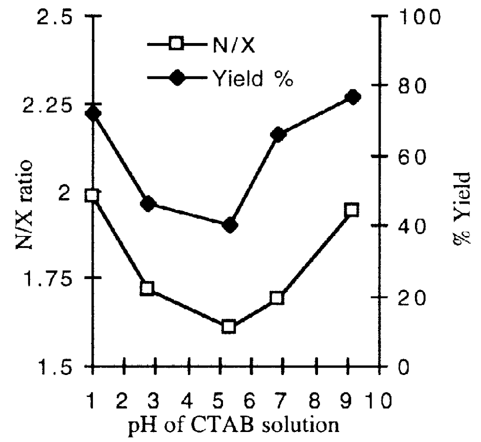

Figure 2

In water at pH 3 the highest *N/X* ratio of 2.3 was observed together with a yield of 75% . Under such conditions, the favourable polarisation of the acrylate molecule in protic media may well stabilise the formation of a micellar aggregate due to the creation of a cationic head group. At even higher acidities however the yield decreases, perhaps reflecting the breakdown of a self aggregate at extremes of pH. Interestingly, when the surfactant CTAB (was present (Figure 2), the highest yields and *N/X* ratio are at the higher and lower acidity range rather than at neutral pH. At low pH the acrylate will be protonated and more readily form a mixed micelle, aligning the protonated ester group with the cationic head group of the surfactant (Figure 3). At high pH, counterion effects (substitution of a bromide ion associated with CTAB for a hydroxide) may influence the aggregate shape or polarise cyclopentadiene thus influencing yield and selectivities.

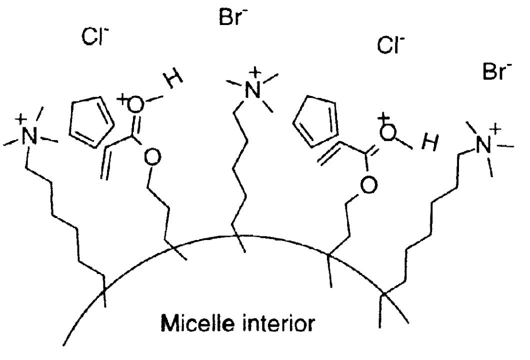

Figure 3

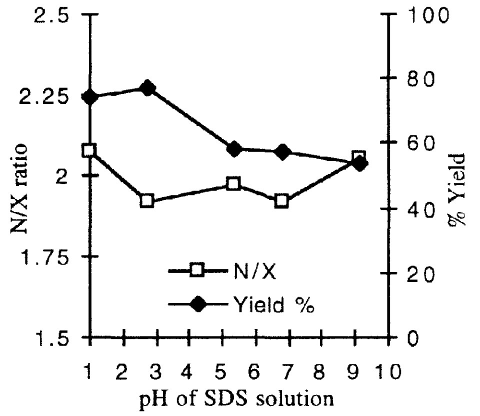

Figure 4

We also monitored the effect of pH on this reaction in the presence of the anionic surfactant SDS. As shown in Figure 4 the effect of pH is not as significant. This is presumably because the major effect of the presence of protons is the replacement of the sodium counterion of the surfactant with a proton in preference to acrylate protonation. We therefore recommend that the optimum pH be established as a routine measure in studies of micellar catalysis.

In summary, the effect of increasing chain length of acrylates in Diels-Alder reactions is a decrease in *endo/exo* product selectivity, and surfactants can clearly have a significant effect on product selectivity and isolated yield especially if used around their **cmc**. However the particular effect which a surfactant can confer appears to depend both on the nature of the substrate and surfactant. Finally, the effect of the pH of the aqueous phase on the reaction can be quite marked, and it is vital that it is monitored to obtain the optimum conditions for the system under investigation.

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