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Reaction in Biphasic Water/Organic Solvent System in the Presence of Surfactant: Inverse Phase Transfer Catalysis versus Interfacial Catalysis

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Abstract—Unexpected results obtained during the study of the influence of surfactant concentration on chalcone epoxidation by H_2O_2 in a water/heptane two-phase system in the presence of a surfactant (DTAB) led us to reconsider the catalytic mechanism of this reaction. Two stirring rates experiments, either low speed (i.e. 100 rpm) or high speed (i.e. 1200 rpm), lead us to discuss kinetic results on the basis of two competitive catalytic processes: an Inverse Phase Transfer Catalysis (IPTC) or an Interfacial Catalysis (IC). © 1999 Elsevier Science Ltd. All rights reserved.

Introduction

The liquid–liquid phase transfer catalysis, discovered by Jarousse[1] in 1951, is a process favouring reactions between a lipophilic substrate, dissolved in an organic phase, with a hydrophilic reactant solubilized in water.

The potential of this catalysis type applied to reactions carried out in biphasic medium were really emphasized by the work of Starks, Liotta, Dehmlow and Makosza, which began in the 1970s.[2] This catalytic procedure is still extensively used in organic synthesis. Two types of liquid–liquid phase transfer catalysis appear from a literature survey. Indeed, the reaction can occur either in the organic phase or in the aqueous one.

We will name the first case ‘Normal’ Phase Transfer Catalysis (NPTC); it is the most widely used. It consists of transferring an anionic reactant from the water phase via a lipophilic ion pair, to the organic phase where the reaction with the lipophilic substrate takes place. The lipophilic ion pair generally corresponds to an anionic reactant associated to either of the following:

1. A lipophilic quaternary onium (tetraalkyl ammonium ion, tetraalkylphophonium) by exchanging its counterion.
2. Its own counterion which has been made lipophilic by complexation with a crown ether.

NPTC has been widely used to carry out a variety of reactions such as substitution, C- and O-alkylation, oxidation and dichloropropanation reactions,[1,2] in simple and cheap conditions.

Another way to effect liquid–liquid phase transfer catalysis consists of transferring the lipophilic substrate into water where it reacts with the hydrophilic reactant. This more recent approach has been called the ‘Inverse Phase Transfer Catalysis’ (IPTC) by Mathias.[3] Several methods have been developed in order to transport the lipophilic substrate into the water phase, such as:

1. The temporary and reversible conversion of the lipophilic substrate into a highly water-soluble ionic intermediate.[3–6]
2. The complexation of a lipophilic substrate by chemically modified cyclodextrins[7] or by water-soluble calixarenes.[8]

Although these methods enhance the reactions rates in biphasic medium, these present two major disadvantages, i.e. the lack of general character and/or the use of costly and not easily accessible catalysts.

Contrary to the above examples, we recently explored a general method dealing with the IPTC. It is based upon the fact that any lipophilic substrate could be transferred into the aqueous phase by means of hydrosoluble surfactants. Indeed, it is well known that micelles formed in the aqueous phase, above the cmc, are able to solubilize a fraction of the substrate in equilibrium with the organic phase. The reaction takes place at the surface of the micelles in the water phase. The reaction product, normally lipophilic, is transferred into the organic phase (Fig. 1).

Keywords: epoxidation; surfactant; phase-transfer catalysis; interface; stirring rate.

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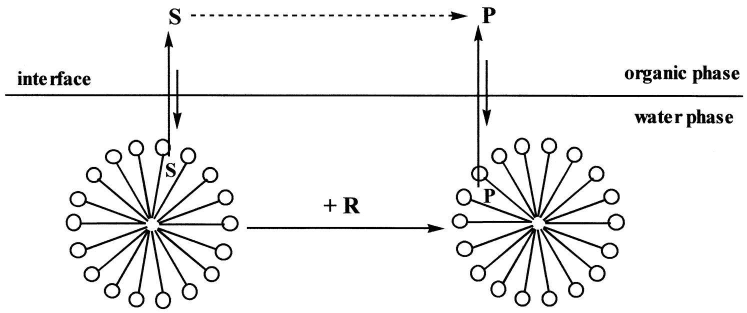


Figure 1. Inverse Phase Transfer Catalysis principle involving a surfactant as catalyst.

In fact, two catalytic processes are involved: (i) an inverse phase transfer—the surfactant allows the transfer of the lipophilic substrate into the water phase; (ii) a micellar catalysis—the charged transition state formed at the micelle surface can be stabilized by the surfactant ionic head groups only in the situation where the charges are opposite.[9]

We proved that this new type of IPTC is of interest especially in the reduction of highly hydrophobic ketones by sodium borohydride[10] and in the epoxidation of α,β-unsaturated ketones by hydrogen peroxide.[11] Both reactions were carried out in a water/heptane biphasic medium.

In order to optimize this last reaction we have examined the influence of the surfactant concentration. Results observed and presented herein, led us to re-examine the IPTC process described above.

Results and Discussion

We have studied the influence of the dodecyltrimethylammonium bromide (DTAB) concentration on the rate epoxidation of the chalcone, which was used as a model. The reaction was carried out by vigorously stirring two equal volumes of the following phases:

organic phase: $[\text{chalcone}]_0=0.1$ M in heptane;
aqueous phase: $[H_2O_2]_0=0.5$ M; $[\text{NaOH}]_0=0.5$ M; [DTAB] varying from 500 to 1 mM.

At different times, an aliquot of the biphasic medium was diluted 100 times in heptane. The absorbance of the solution was measured at 300 nm, as chalcone was the only species absorbing at this wavelength ($\varepsilon=22400\ \text{M}^{-1}\ \text{cm}^{-1}$ in heptane).[12] Absorbance variations for each DTAB concentration, and without DTAB, are represented in Fig. 2.

As expected, the decrease of the surfactant concentration markedly reduces the reaction rate. Indeed, the lower its concentration, the lower its solubilizing power as well as its micellar catalysis efficiency. However, it was surprising to observe catalytic effects with a surfactant concentration as low as 1mM even though the presence of 0.5 M NaOH lowers the cmc of DTAB (a cmc value of 0.64 mM in 0.5M NaOH was measured, while it is equal to 14.4 mM in pure water).[10] Obviously, at 1 mM in DTAB, the micellar concentration together with the resulting chalcone solubilizing capacity seemed too low to induce a significant IPTC process. Under vigorous stirring an emulsion was observed; we assumed that the large interface separating the two phases would play an important role.

To check this point, we repeated the chalcone epoxidation

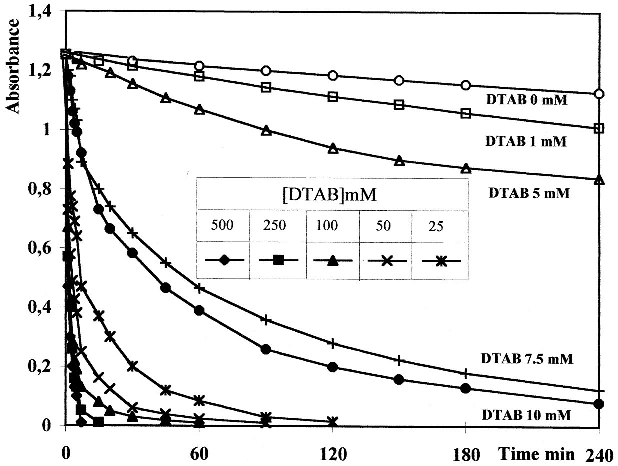


Figure 2. Interfacial Catalysis: absorbance variations (λ=300 nm) versus time for the epoxidation of chalcone at several DTAB concentrations in biphasic medium (heptane/water 1/1) under vigorous stirring (1200 rpm).

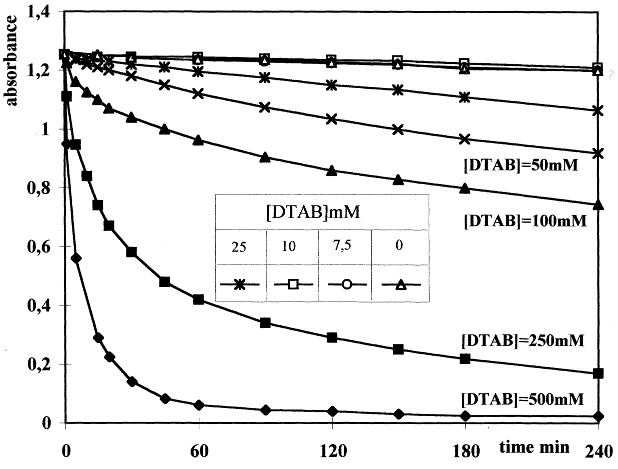


Figure 3. Inverse Phase Transfer Catalysis: absorbance variations (λ=300 nm) versus time for the epoxidation of chalcone at several DTAB concentrations in biphasic media (heptane/water 1:1) under slow stirring (100 rpm).

Table 1. Initial rates of the epoxidation reaction of chalcone versus DTAB concentration at two stirring rates (100 and 1200 rpm)

[DTAB] (mM)	500	250	100	50	25	10
r_0 (fast)	1.5×10^{-1}	1.1×10^{-1}	8.0×10^{-2}	6.2×10^{-2}	2.2×10^{-2}	5.2×10^{-4}
r_0^{rel} (fast)	288	212	154	119	42	1
r_0 (slow)	2.0×10^{-2}	5.0×10^{-3}	6.0×10^{-4}	2.0×10^{-4}	6.1×10^{-5}	1.3×10^{-5}
r_0^{rel} (slow)	1538	385	46	15	4.7	1

reaction under the same experimental conditions but without vigorous stirring. We applied slow magnetic stirring, just enough to avoid a concentration gradient in each phase.

In such conditions an emulsion is not formed and the interface area between the two phases is equal to the section area of the used flask. Measuring the absorbance of diluted aliquots of the upper heptane phase monitored the reaction.

Variations of the optical density versus time are plotted in Fig. 3 at several DTAB concentrations.

It appears that the reaction is strongly accelerated when DTAB concentration increases up to 500 mM. However, the reaction rate is not significantly modified if the surfactant concentration is ranging from 0 to 10 mM. We thought that under slow stirring conditions the results fit in with IPTC as presented above (Fig. 1). The higher the surfactant concentration, the higher the solubilizing power and then the more efficient the catalytic effect.

However, another way to explain the observed catalytic effect could consist of the transfer of the HOO^- reactive anion in the organic phase via ion pairing with the dodecyltrimethylammonium cation, according to a normal PTC process. To distinguish between these two possibilities we completed the three following experiments:

1. Fifteen millilitres of heptane were equilibrated with 15 ml of water containing 0.5 M H_2O_2, 0.5 M NaOH and 0.1 M DTAB. After 4 h the two phases were separated and 10 ml of the heptane phase was dry evaporated under vacuum. No detectable traces of solute were found in heptane. That means that under the conditions used dodecyltrimethylammonium is not able to transfer into heptane with either bromine anion or hydroperoxide anion.
2. Tetrabutylammonium hydrogenosulfate (TBAHS), well known as an efficient normal phase transfer catalyst, was tested to carry out chalcone epoxidation (4 ml of 0.1 M chalcone in heptane and 4 ml of water containing 0.5 M H_2O_2, 0.5 M NaOH and 0.1 M TBAHS). The percentages of consumed chalcone at $t=2$ h were only 5 and 25% under slow stirring (100 rpm) and vigorous stirring (1200 rpm), respectively. In both cases, the reaction is much slower than when DTAB is used at the same concentration (see Figs. 1 and 2). Obviously, DTAB, which is more efficient than TBAHS, acts in a different way.
3. Sodium dodecylsulfate (SDS), an anionic surfactant, was also evaluated in the same conditions as above using TBAHS ([SDS]=0.1 M). As already observed in the reduction of hydrophobic ketones by sodium borohydride,[10] SDS catalysed the epoxidation reaction under either slow or high stirring speed. The percentages of epoxide formed at $t=2$ h were 17 and 31%, respectively. It appears that SDS is a better catalyst than TBAHS. However, it is clear that SDS cannot catalyse the reaction by transferring HOO^- either at the interface or into heptane, as does TBAHS.

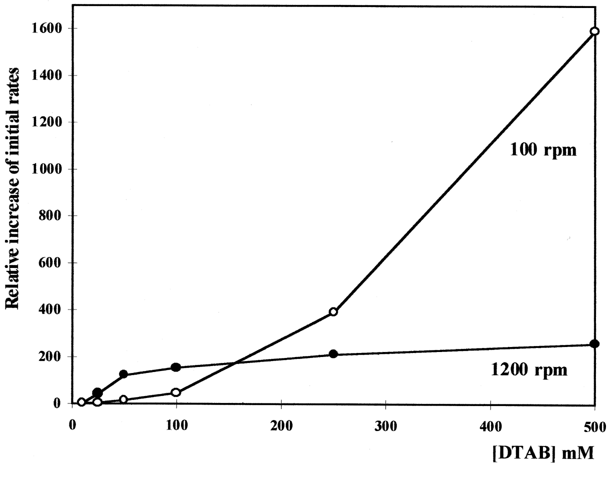


Figure 4. Relative increase of initial rates versus the surfactant concentration for the epoxidation reaction realized by IPTC or IC. [chalcone]=0.1 M; [NaOH]=0.5 M; $[H_2O_2]$=0.5 M; 25°C.

All these results agree with the competition between two catalytic processes, the predominant one depending upon the stirring conditions.

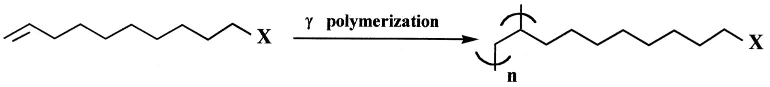
Finally, for each surfactant concentration, the initial rate (r_0) of the epoxidation reaction was determined under fast (1200 rpm) and slow (100 rpm) stirring rates. Values are reported in Table 1.

From this table, it is worthwhile pointing out the following observations:

1. Whatever the stirring speed, increase of the surfactant concentration enhances the rate of the epoxidation reaction.
2. The initial rates ratio of this reaction realized in the same surfactant concentrations but with different stirring speed decreases when the DTAB concentrations increases. In other words, initial rates performed by IPTC or IC get closer as the surfactant concentration increases.

The relative increase of initial rates of the epoxidation reaction performed with slow stirring (100 rpm) or with fast stirring (1200 rpm) compared with the initial rate measured at [DTAB]=10 mM is represented in Fig. 4.

From the plots presented in Fig. 4, we note that the influence of surfactant concentration on the reaction rate is more



$-X = -CH_2N^+(CH_3)_3/Br^-$ or $-CO_2^-/Na^+$

Scheme 1.

important in the case of IPTC than with IC. That agrees with the difference of mechanism for these two processes. Thus, in the case of the IPTC, the reaction rate is determined by the micellar concentration in the aqueous phase; consequently, the increase of the surfactant concentration strongly enhances the reaction rate. In the case of IC the reaction takes place at the interface. To cover this surface with a monomolecular layer, only very weak quantities of surfactant are needed.[13] As soon as this surface is covered, the reaction rate is no longer influenced by surfactant concentration.

So it appeared that under slow-speed stirring, catalysis occurs mainly through an IPTC process. The surfactant operates both in transferring the substrate in the aqueous phase via micelles (provided micellar concentration is high enough) and in stabilizing the transition state by electrostatic interaction (micellar catalysis). On the contrary, under vigorous stirring a large interfacial area results from the formation of an emulsion. This allows a stronger encounter probability of the lipophilic substrate with the hydrophilic reactant. The reaction takes place mainly at the interface. The surfactant reduces the interfacial tension, increases the interfacial area and again stabilizes the negative transition state formed, at the interface, close to the ammonium groups of the surfactant. It is an Interfacial Catalysis (IC) process. In this case, a small amount of surfactant is enough to promote the catalytic pathway.

A question arises in the case where slow stirring is applied. Actually, a mass transfer involved by IPTC could be the rate limiting step, as the stirring speed is low. To answer this question, we carried out the reaction in the following monophasic conditions, in water:

$[H_2O_2]_0=0.5$ M; $[NaOH]_0=0.5$ M; $[\text{chalcone}]_0=0.01$ M and $[\text{DTAB}]=0.1$ M.

The epoxidation is very quickly achieved (less than 1 min). Obviously, under biphasic conditions, mass transfer contributes to limit the overall transformation rate. Nevertheless the reaction takes place mainly within the aqueous phase as an increase of the micellar concentration enhances the reaction rate.

It is worthwhile mentioning that a previously reported behaviour of polymerized surfactants[10] sustains our hypothesis. These polymeric species were obtained by polymerization under γ-irradiation of aqueous micellar solution of ω-unsaturated tensides (Scheme 1).

We observed that polymerization increased the solubilizing power of a hydrophobic substrate in water.[14] Moreover polymerized micelles were more efficient than their non-polymerized analogues in promoting micellar catalysis in monophasic aqueous conditions.[14] Surprisingly, when used in a biphasic medium (water/heptane), polymerized micelles were less efficient[10] than their non-polymerized analogues in catalysing the reduction of hydrophobic ketones by sodium borohydride under vigorous stirring.

At the same time, we observed that polymerized species have no effect upon interfacial tension[15] because they are unable to form a monolayer at the interface. As a consequence, even under vigorous stirring, they do not produce emulsion.

Under high-speed stirring, all these results lead to the following conclusions:

- With polymerized surfactants, only the IPTC process is involved. This explains their lower efficiency as catalysts under biphasic conditions, despite their higher aptitude to solubilize hydrophobic substrates in water and to increase the micellar catalysis.
- On the contrary, ‘normal’ non-polymerized surfactants operate via the more efficient IC process. The IPTC process may also intervene, but only as a minor complementary pathway.

Further examination of the proposed Interfacial Catalytic (IC) process is underway, along with its application to additional reaction.

Experimental

Dodecyltrimethylammonium bromide (DTAB), chalcone, sodium hydroxide and 30% hydrogen peroxide were obtained from commercial sources. UV studies were performed on a SAFAS-170 spectrophotometer.

General procedure for epoxidation reactions

Reactions in two-phase media were studied according to the following protocol. Four millilitres of the organic phase (0.1 M chalcone in heptane) were added to 4 ml of the aqueous phase. The aqueous phase was prepared just before the beginning of the reaction by mixing together 2 ml of 1.0 M H_2O_2, 1 ml of 2.0 M NaOH and 1 ml of either water or aqueous solution of DTAB at concentrations ranging from 1 to 500 mM. The mixture is quickly stirred at the appropriate speed (100 or 1200 rpm) in a jacketed reactor thermostated at 25°C. At a given time, 20 μl of the emulsion (1200 rpm) or 10 μl of the upper heptane phase (100 rpm) were withdrawn and poured into a tube containing 2 ml of heptane. In the first case the tube was shaken and allowed to stand for a few minutes in order to separate the small amount of aqueous phase from the organic one. In both cases the UV absorbance of the heptane solution was measured in a cuvette (0.1 cm) equilibrated cell holder (25°C) of a SAFAS-170 spectrophotometer.

The concentration of chalcone was thus monitored as a function of time. Each absorbance value reported is the mean of at least three independent readings differing by less than 5%.

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12. To confirm the relevance of spectrometric observations, several experiments were achieved. In particular: (a) Epoxide concentration can be monitored at 245 nm (ϵ=16973 in heptane) concurrently with the ketone concentration measured at 300 nm. For a given kinetic, it is worthwhile to mention that half-life times are very close for chalcone disappearance and epoxide formation, excluding a significant accumulation of any intermediate. This result is also confirmed by the observation of isosbestic points when a series of spectra recorded versus time are superimposed. (b) As chalcone could react with OH^- giving a retrograde aldol reaction,[16] we tested the contribution of this side-reaction in the absence of hydrogen peroxide under the following conditions: $[\text{chalcone}]_0=0.1$ M; [DTAB]=0.1 M; $[\text{NaOH}]_0=0.03$ or 0.50 M; stirring speed=100 or 1200 rpm. All results reported in our paper were obtained with 0.5 M NaOH, but because of the acidic character of H_2O_2 the initial OH^- concentration can be evaluated as close to 0.03 M according the pK_a of H_2O_2 (11.13).[16] Whatever the stirring speed, with $[\text{NaOH}]_0=0.03$ M, no significant spectral change is detectable over a period of 4 h. Within the same period of time and with $[\text{NaOH}]_0=0.5$ M, the percentage of chalcone transformed is only 10 and 18% at 100 and 1200 rpm stirring speed, respectively. It can be considered that the side-reaction of chalcone with $[OH^-]$ is quite slow compared with the epoxidation rate as in the presence of 0.5 M H_2O_2, $[OH^-]$ being always lower than 0.5 M.

13. At 1200 rpm, the surfactant quantity necessary to stabilize the interface is very weak. A simple calculation shows that 4.3×10^{14} molecules are sufficient to cover 1 cm^2 of the surface.[17] For a 10 mM DTAB concentration, there are in 2 ml of the aqueous phase 6.02×10^{21} molecules able to cover, in theory, 1.4×10^{7} cm^2. Clearly any surfactant increase cannot proportionally increase the interface area. At this level of concentration, this latter is certainly more influenced by the stirring rate than by the surfactant concentration.

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