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## Mechanism of Dehydrobromination of 1,2-Dibromo-1-phenylethane under Conditions of Phase-Transfer Catalysis

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**Abstract**—Selective dehydrobromination of 1,2-dibromo-1-phenylethane to  $\alpha$ -bromostyrene was effected under conditions of phase-transfer catalysis in systems containing KOH, toluene, and tetraalkylammonium bromides. The high selectivity of the catalytic systems originates from stabilization by lipophilic cation of the phase-transfer catalyst of a E1cb-like transition state in the E2 mechanism. In the presence of a catalytic amount of lipophilic alcohols, phenylacetylene was obtained. Substrate activation by alcohol molecules is explained by enhancement of the acceptor power of halogen atoms due to solvation and by increased mobility of hydrogen atoms.

Hydrogen halide elimination from alkyl halides under conditions of phase-transfer catalysis (PTC) attracts a keen interest, as follows from the data summarized in [1]. Elimination reactions in two-phase systems can be effected with various bases and solvents. From the viewpoint of a classical version of PTC, the most interesting are systems containing alkali metal hydroxides and weakly polar organic solvents which are incapable of dissolving those bases in the absence of a phase-transfer catalyst. In order to substantiate the mechanism of elimination it is necessary to localize the reaction zone (whether the reaction occurs in the organic or aqueous phase or in the third phase formed by the catalyst itself [2]) and to determine whether does the process involve deprotonation stage at the phase boundary [3] or it occurs intermolecularly in a donor–acceptor complex formed by the base and the substrate [4]. There are no unambiguous concepts on the nature of catalytic activity of weak organic acids (HY), such as alcohols and glycols. It is assumed that either HY gives rise to lipophilic anion  $Y^-$ , which is a stronger base than hydroxide ion and is extracted into organic phase more readily [5] or the reaction proceeds through a cyclic complex formed from quaternary ammonium salts, alcohol, substrate, and base [6].

In the present work we studied the mechanism of the chemical stage of dehydrobromination of 1,2-dibromo-1-phenylethane in two-phase systems liquid–liquid (l/l) with a 50% aqueous solution of KOH and

liquid–solid (l/s) with finely dispersed KOH in the presence of tetraalkylammonium bromides as phase-transfer catalysts; toluene was used as organic phase. Depending on the base and solvent nature, hydrogen halide elimination from  $\alpha$ -aryl-substituted alkyl halides follows either E1 ( $S_N1$  substitution) or E2 mechanism with an E1-like transition state ( $S_N2$  substitution).  $\beta$ -Aryl-substituted alkyl halides undergo elimination according to E1cb mechanism or E2 mechanism with an E1cb-like transition state ( $S_N2$  substitution) [7]. 1,2-Dibromo-1-phenylethane is a substrate which, depending on the conditions of the first dehydrobromination stage (elimination of one HBr molecule), could give rise to all possible elimination mechanisms (E1, E2, and E1cb). The E1 mechanism should favor formation of  $\beta$ -bromostyrene, while  $\alpha$ -bromostyrene should be obtained along the E1cb path.

Thus, it becomes possible to determine which mechanism of dehydrohalogenation is favored by phase-transfer conditions with participation of lipophilic cation ( $Q^+$ ) of the phase-transfer catalyst. For comparison, dehydrobromination of 1,2-dibromo-1-phenylethane was also performed in a classical homogeneous system with potassium *tert*-butoxide as base and *tert*-butyl alcohol as solvent.

In all the examined systems (Table 1), the dehydrobromination of 1,2-dibromo-1-phenylethane follows overall second-order kinetics (the effects of substrate concentration and amount of base on the reaction rate

**Table 1.** Efficiency and selectivity of dehydrobromination of 1,2-dibromo-1-phenylethane in homogeneous and heterogeneous (PTC) systems

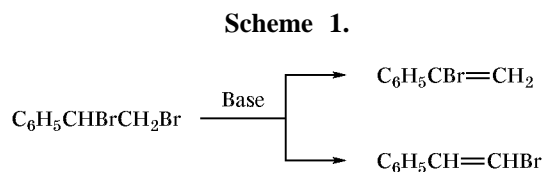
System <sup>a</sup>	$k \times 10^2$ , l mol <sup>-1</sup> min <sup>-1</sup>	Selectivity of elimination, %			Selectivity of nucleophilic substitution, %
		$\alpha$ -bromo-styrene	$\beta$ -bromo-styrene	phenyl-acetylene	
Homogeneous, <i>t</i> -BuOK/ <i>t</i> -BuOH	3.30	32.3	3.2	–	Ethers 64.5 (43 and 21.5)
PTC l/l, catalyst <b>I</b> , organic phase toluene	0.62 <sup>b</sup>	96.5	3.1	0.4	Traces of acetophenone
PTC l/s, catalyst <b>II</b> , organic phase toluene	1.50 <sup>b</sup>	94.4	4.2	1.4	Traces of acetophenone

<sup>a</sup> Phase-transfer catalysts: cetyltrimethylammonium bromide (**I**) and tetrabutylammonium bromide (**II**).

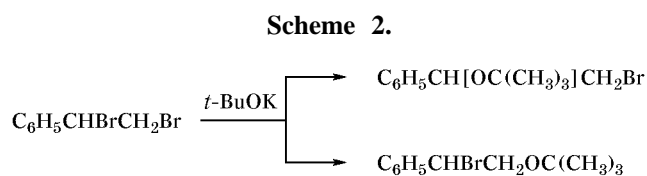
<sup>b</sup> Calculated on the “arbitrary” concentration of KOH (M) in the organic phase.

will be discussed elsewhere). Therefore, the rate constant for the homogeneous reaction ( $k$ ) was calculated by the second-order equation. Mathematical description of PTC reactions should take into account the distribution of phase-transfer catalyst [in our case, cetyltrimethylammonium bromide (**I**) or tetrabutylammonium bromide (**II**)] between the aqueous and organic phases and phase boundary, as well as the ion exchange constants for Br<sup>-</sup> and OH<sup>-</sup> (selectivity constants). Therefore, for two-phase systems l/l and l/s we calculated an arbitrary second-order rate constant by dividing the pseudofirst-order rate constant by the overall amount of KOH (mol) in the system, reduced to the volume of the organic phase (l). The results given in Table 1 show that the system *t*-BuOK/*t*-BuOH is more active than heterogeneous l/l and l/s systems containing KOH and phase-transfer catalyst; the l/s system is more active than l/l.

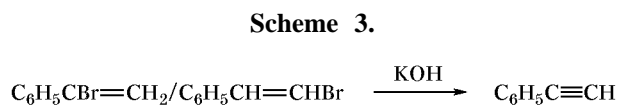
An important aspect is the selectivity of formation of elimination products and those resulting from nucleophilic substitution as side process. According to the GLC data (Table 1), elimination in the system *t*-BuOK/*t*-BuOH gives mainly  $\alpha$ -bromostyrene and a small amount of  $\beta$ -bromostyrene (the latter was identified using a mixture of the *cis* and *trans* isomers; Scheme 1).



Also, nucleophilic substitution products are formed in the system according to Scheme 2.



It should be noted that the contribution of nucleophilic substitution (two ethers are formed) in the system *t*-BuOK/*t*-BuOH exceeds the contribution of the elimination process. In the l/l and l/s systems containing KOH and phase-transfer catalyst, elimination occurs according to Scheme 1, yielding mainly  $\alpha$ -bromostyrene, whereas alcohols (nucleophilic substitution products) cannot be determined quantitatively (Table 1). Also, PTC systems give rise to formation of small amounts of phenylacetylene (Table 1) as dehydrobromination product of  $\alpha$ - and  $\beta$ -bromostyrenes (Scheme 3).



Thus, a considerable advantage of dehydrobromination of 1,2-dibromo-1-phenylethane under conditions of phase-transfer catalysis in liquid–liquid and liquid–solid systems against the homogeneous reaction in the system *t*-BuOK/*t*-BuOH is high selectivity of formation of  $\alpha$ -bromostyrene (94–96%). This result is consistent with published data on the formation of  $\alpha$ -bromostyrene in the system benzene–1,2-dibromo-1-phenylethane–Aliquat 336 in 83% yield (reaction time 3 h) [8] and in the system containing an aqueous solution of KOH and catamine AB with a selectivity of 85% in  $\alpha$ -bromostyrene and 5% in

$\beta$ -bromostyrene [3]. The high selectivity of formation of  $\alpha$ -bromostyrene under conditions of phase-transfer catalysis is explained by replacement of *t*-BuOK as a base by KOH and by the presence of an interphase carrier having a lipophilic cation  $Q^+$ . In order to elucidate the role of lipophilic cation  $Q^+$  in the mechanism of elimination (chemical stage) in two-phase systems (l/l and l/s) we used various organic solvents and cetyltrimethylammonium bromide as phase-transfer catalyst (Table 2).

The data given in Table 2 show that toluene is incapable of dissolving KOH (almost no reaction is observed in the absence of phase-transfer catalyst). Therefore, phase-transfer catalyst ensures not only selective formation of  $\alpha$ -bromostyrene but also hydroxide ion transfer from the aqueous or solid phase to the phase boundary and partially to the bulk organic phase. Such solvents as dimethyl sulfoxide and pyridine dissolve KOH, and the l/l and l/s systems are active in the absence of phase-transfer catalyst, but the yield of  $\alpha$ -bromostyrene (56–73%) insignificantly exceeds the yield of  $\beta$ -bromostyrene (22–38%). Addition of phase-transfer catalyst to the above systems considerably reduces the yield of  $\beta$ -bromostyrene (to 2–6%) and increases the yield of  $\alpha$ -bromostyrene (to 91–98%). These data unambiguously indicate that lipophilic cation  $Q^+$  not only acts as interphase carrier in two-phase systems but also directly participates in the mechanism of chemical elimination stage. Insofar as lipophilic cation  $Q^+$  could favor stabilization of essentially carbanionic transition state (E1cb) of the E2 mechanism rather than of carbocationic transition state (E1), the major product of 1,2-dibromo-1-phenylethane dehydrobromination under PTC conditions is  $\alpha$ -bromostyrene.

We can conclude that the most appropriate substrates for elimination in two-phase systems with a lipophilic cation  $Q^+$  are those having a hydrogen atom activated by electron-acceptor substituent or located in the benzylic position. This conclusion is consistent with published data [1].

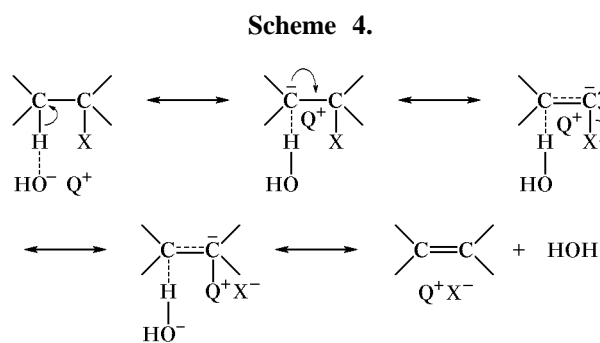
Replacement of 1,2-dibromo-1-phenylethane by 1,2-dichloro-1-phenylethane in l/l and l/s two-phase systems containing KOH, toluene, and phase-transfer catalyst leads to increased yield of  $\alpha$ -chlorostyrene as compared to  $\alpha$ -bromostyrene (Table 3). Presumably, the  $\alpha$ -hydrogen atom in the chlorine-containing substrate is more labile due to stronger  $-I$  effect of chlorine as compared to bromine. This leads to increased carbanionic character of E1cb-like transition state in the E2 mechanism. Although chloride ion is inferior to  $Br^-$  in nucleofugality, the rate of elimination increases and the yield of  $\beta$ -chlorostyrene is lower than the yield of  $\beta$ -bromostyrene (Table 3).

**Table 2.** Yields of 1,2-dibromo-1-phenylethane dehydrobromination products (%) in the presence of cetyltrimethylammonium bromide (**I**) as phase-transfer catalyst in various solvents

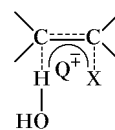
Solvent	$\alpha$ -Bromo-styrene		$\beta$ -Bromo-styrene		Phenyl-acetylene	
	l/l	l/s	l/l	l/s	l/l	l/s
Toluene <sup>a</sup>	0.6	0.8	0.1	–	–	–
Toluene	67.8	73.9	2.1	3.5	0.4	0.8
DMSO <sup>a</sup>	56.7	73.6	34.2	21.7	–	–
DMSO	96.7	97.8	2.9	2.0	Traces	Traces
Pyridine <sup>a</sup>	56.3	72.9	37.3	24.3	–	–
Pyridine	91.0	93.1	5.3	5.9	0.1	0.7

<sup>a</sup> In the absence of phase-transfer catalyst.

Probably, in systems containing an aprotic dipolar solvent and a strong organic base, substrates having a highly labile hydrogen atom are capable of giving rise to pure E1cb mechanism. In this case, intermediate carbanion and lipophilic cation of the phase-transfer catalyst form an ion pair. However, aprotic dipolar solvents are extremely rarely used in phase-transfer reactions, for they are expensive, toxic, and difficult to regenerate. There are no reasons to assume pure E1cb mechanism in classical PTC systems based on alkali metal hydroxides and weakly polar organic solvents like toluene. The role of lipophilic cation  $Q^+$  in the stabilization and evolution of a carbanionic E1cb-like transition state may be illustrated by Scheme 4.



The general scheme of stabilization of carbanionic transition state by lipophilic cation is shown below:



**Table 3.** Yields (%) of  $\alpha$ -halostyrenes,  $\beta$ -halostyrenes, and phenylacetylene from 1,2-dibromo-1-phenylethane and 1,2-dichloro-1-phenylethane

Substrate	Catalyst <sup>a</sup>	$\alpha$ -Halostyrene		$\beta$ -Halostyrene		Phenylacetylene	
		l/l	l/s	l/l	l/s	l/l	l/s
1,2-Dibromo-1-phenylethane	<b>I</b>	67.8	73.9	2.1	3.5	0.4	0.8
	<b>II</b>	58.8	83.3	2.9	3.7	0.4	1.2
1,2-Dichloro-1-phenylethane	<b>I</b>	93.0	93.4	0.9	1.3	0.5	1.8
	<b>II</b>	92.0	96.9	1.0	1.3	0.5	1.5

<sup>a</sup> Phase-transfer catalysts: cetyltrimethylammonium bromide (**I**) and tetrabutylammonium bromide (**II**).

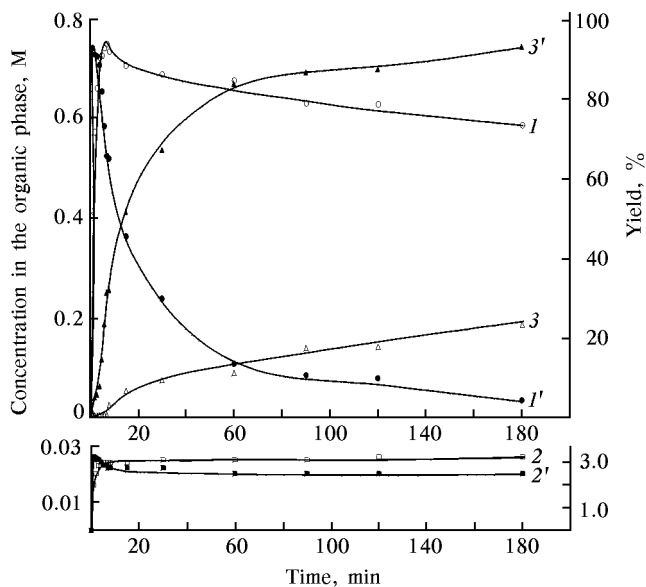
According to this scheme, electron density transfer in the transition state is accompanied by movement of the cation  $Q^+$  toward the site with maximal localization of the negative charge. Thus, in the initial interaction between the ion pair  $Q^+ OH^-$  with substrate the cation  $Q^+$  acts as a carrier which transfers the base to the substrate; its further movement toward the halogen atom X facilitates nucleofuge departure as  $Q^+ X^-$  ion pair.

Elimination of hydrogen under phase-transfer catalysis can be facilitated by addition of phenols, alcohols, or carboxylic acid salts [9]. If the departing group X is an anion, the promoting additive favors heterolytic dissociation of the C–X bond via hydrogen bonding and transition from the E2 mechanism to E1 [7]. However, we believe that catalytic amounts

of such additives, e.g., alcohols, favor stabilization of E1cb-like transition state in the E2 mechanism. Interaction of alcohol molecule with bromine atoms in 1,2-dibromo-1-phenylethane enhances their acceptor properties and  $-I$  effect without essential heterolysis of the C–Br bond in a nonpolar solvent (toluene). This leads to increased mobility of the  $\alpha$ -hydrogen atom and favors formation of a carbanionic E1cb-like transition state. Moreover, activation of  $\alpha$ -bromostyrene with alcohol facilitates its dehydrobromination to phenylacetylene. The data in Table 4 characterize the effect of some lipophilic alcohols, namely 2-phenyl-2-propanol (**III**), 2-methyl-2-propanol (**IV**), and 2-methyl-2-butanol (**V**), on the yield of elimination products from 1,2-dibromo-1-phenylethane in l/l and l/s systems containing KOH, cetyltrimethylammonium bromide (**I**), and toluene as solvent. It is seen that in the absence of phase-transfer catalyst alcohols exhibit no catalytic effect and that in the presence of phase-transfer catalyst all the examined alcohols accelerate transformation of the substrate into  $\alpha$ -bromostyrene and its further dehydrobromination to phenylacetylene.

Figure shows typical kinetic curves for accumulation of elimination products in l/l and l/s systems containing tetrabutylammonium bromide (**II**) and 2-methyl-2-butanol (**V**). Selective transformation of the substrate into  $\alpha$ -bromostyrene occurs at a very high rate (within 1 min in l/s system), and  $\alpha$ -bromostyrene is then converted into phenylacetylene. The l/s system is more active, and the yield of phenylacetylene reaches 85% in 1 h.

Thus, study of the dehydrobromination of 1,2-dibromo-1-phenylethane under conditions of phase-transfer catalysis showed that lipophilic cation  $Q^+$  of the catalyst stabilizes E1cb-like transition state in the E2 mechanism. Elimination of hydrogen atom is favored by addition of catalytic amounts of lipophilic alcohols which enhance acceptor power of the halogen atoms via solvation.



Kinetic curves for formation of (1, 1')  $\alpha$ -bromostyrene, (2, 2')  $\beta$ -bromostyrene, and (3, 3') phenylacetylene in two-phase systems (1–3) liquid–liquid and (1'–3') liquid–solid.

**Table 4.** Yields (%) of 1,2-dibromo-1-phenylethane dehydrobromination products in the presence of alcohols

Alcohol	Phase-transfer catalyst	$\alpha$ -Bromostyrene		$\beta$ -Bromostyrene		Phenylacetylene	
		l/l	l/s	l/l	l/s	l/l	l/s
2-Phenyl-2-propanol ( <b>III</b> )	–	3.9	2.4	–	2.1	–	–
–	<b>I</b>	67.9	73.9	2.1	3.5	0.4	0.8
2-Phenyl-2-propanol ( <b>III</b> )	<b>I</b>	95.6	82.7	34.2	21.7	–	–
2-Methyl-2-propanol ( <b>IV</b> )	<b>I</b>	94.9	77.0	3.2	3.6	0.5	11.8
2-Methyl-2-butanol ( <b>V</b> )	<b>I</b>	81.3	77.9	2.9	2.8	0.5	13.6

## EXPERIMENTAL

The reaction mixtures were analyzed by GLC on a Kristall-2000M chromatograph equipped with a flame-ionization detector (SE-30 quartz capillary column, 22 m $\times$ 0.32 mm; isothermal mode, oven temperature 170°C; injector and detector temperature 200°C; split ratio 1:20; time 7 min; carrier gas argon, inlet pressure 5 atm).

The dehydrohalogenation was performed in a glass reactor equipped with a jacket (to maintain a constant temperature) and a reflux condenser. The reaction mixture was vigorously stirred with a magnetic stirrer.

**Homogeneous dehydrobromination of 1,2-dibromo-1-phenylethane.** Metallic potassium, 0.005 mol (0.195 g), was dissolved in 10 ml of *tert*-butyl alcohol at room temperature. The resulting solution of potassium *tert*-butoxide in *tert*-butyl alcohol was added to a solution of 0.005 mol (1.32 g) of 1,2-dibromo-1-phenylethane in 10 ml of *tert*-butyl alcohol, heated to 80°C. The mixture was heated for 8 min at 80°C at a stirring speed of 2100 rpm.

**Catalytic dehydrohalogenation of 1,2-dihalo-1-phenylethanes in two-phase systems.** *a. Liquid-liquid.* To 4 ml of a solution of 1,2-dibromo-1-phenylethane or 1,2-dichloro-1-phenylethane at a concentration of 0.8 M in appropriate solvent (toluene, DMSO, or pyridine) we added  $4 \times 10^{-6}$  mol of phase-transfer catalyst, cetyltrimethylammonium bromide (**I**) ( $1.5 \times 10^{-3}$  g) or tetrabutylammonium bromide (**II**) ( $1.3 \times 10^{-3}$  g); 4 ml of a 50% aqueous solution of KOH (13.45 M) was then added (the volume ratio of the aqueous and organic phases was 1:1).

While studying the effect of addition of alcohols, the volume of the substrate (1,2-dibromo-1-phenylethane) solution in toluene (0.8 M) was increased to 10 ml, and the amount of cetyltrimethylammonium bromide, to  $1 \times 10^{-5}$  mol ( $3.6 \times 10^{-3}$  g); to the resulting mixture we added  $1 \times 10^{-5}$  mol of the corresponding

alcohol and 10 ml of a 50% aqueous solution of KOH. The reaction time was 8 min.

In the study of the kinetics of dehydrobromination,  $8 \times 10^{-6}$  mol of catalyst **II** and  $8 \times 10^{-6}$  mol of alcohol **V** were added to a solution (4 ml) of 1,2-dibromo-1-phenylethane in toluene (0.8 M), and 4 ml of a 50% aqueous solution of KOH was added.

In all experiments, the reaction temperature was 80°C, stirring speed 2100 rpm.

*b.* A solution (4 ml) of 1,2-dibromo-1-phenylethane or 1,2-dichloro-1-phenylethane ( $c = 0.8$  M) in appropriate solvent (toluene, DMSO, or pyridine) was mixed with  $4 \times 10^{-6}$  mol of catalyst **I** or **II**, and  $2.5 \times 10^{-2}$  mol (1.4256 g) of finely powdered (and screened through a sieve; grain size 400  $\mu$ m) solid KOH and  $3.9 \times 10^{-4}$  mol ( $7 \times 10^{-3}$  ml) of water were added.

While studying the effect of catalytic amounts of alcohols, the substrate (1,2-dibromo-1-phenylethane) solution in toluene (0.8 M) was adjusted to a volume of 10 ml, and the amount of catalyst **I** was increased to  $1 \times 10^{-5}$  mol. To the resulting mixture we added  $1 \times 10^{-5}$  mol of appropriate alcohol,  $6.4 \times 10^{-2}$  mol (3.654 g) of KOH, and  $1 \times 10^{-3}$  mol ( $1.8 \times 10^{-2}$  ml) of water. The reaction time was 8 min, and the process was complete in 10 min.

In the study of the kinetics of dehydrobromination, 4 ml of a 0.8 M solution of 1,2-dibromo-1-phenylethane in toluene was mixed with  $8 \times 10^{-6}$  mol of catalyst **II** and  $8 \times 10^{-6}$  mol of alcohol **V**. Finely powdered (and screened through a sieve; grain size 400  $\mu$ m) solid KOH,  $2.5 \times 10^{-2}$  mol (1.4256 g), and  $3.9 \times 10^{-4}$  mol ( $7 \times 10^{-3}$  ml) of water were added.

In all experiments, the reaction temperature was 70°C, and the speed of stirring, 1500 rpm.

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