



Dichlorocarbene addition to allyl phenyl ether under phase-transfer catalysis conditions—A kinetic study

Venugopal Rajendran^{a,*}, Maw-Ling Wang^b

^a Department of Chemistry, Pachaiyappa's College for Men, Kanchipuram, Tamil Nadu 631501, India

^b Department of Environmental Chemistry, Hung Kuang University, Shalu, Taichung County, Taiwan, ROC

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ABSTRACT

The kinetics of dichlorocarbene addition to allyl phenyl ether have been studied under phase-transfer catalytic conditions using aqueous sodium hydroxide as the base and benzyltriethylammonium bromide as a phase-transfer catalyst. The reaction was carried out at 35 °C under pseudo-first-order conditions by keeping aqueous sodium hydroxide and chloroform in excess and was monitored by GC. The effect of various experimental parameters on the rate of the reaction has been studied and based on the results obtained, a suitable mechanism is proposed.

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1. Introduction

Phase-transfer catalysis (PTC) is a technique for conducting heterogeneous reactions where the reagents are located in different phases. In order for PTC to take place, the quaternary ammonium cation must effectively transport the reactant anion from the aqueous phase through the interfacial region into the organic phase. Undoubtedly, PTC offers many substantial advantages for the practical execution of numerous reactions. Its wide application in organic synthesis is well deserved [1–10].

Dihalocyclopropanes are very useful compounds that can be reduced to cyclopropane derivatives, treated with magnesium or sodium to give allenes and can be converted to a number of other products [11]. Literature reports of the generation and reaction of dichlorocarbene stress the necessity of operating under strictly anhydrous conditions, because of the ready and rapid hydrolysis of dichlorocarbene. Many of these difficulties are eliminated when the reactions are carried out in biphasic systems of concentrated sodium hydroxide in the presence of benzyltriethylammonium bromide (BTEAB) as a phase-transfer catalyst. Similar studies employing PTCs for the generation of dichlorocarbene have been reported earlier by several authors [11–21].

The main purpose of this study is to synthesize dichlorocyclopropane from the reaction of allyl phenyl ether and chloroform in an alkaline solution of NaOH/organic solvent two-phase medium under PTC conditions. The active dichlorocarbene was generated from the reaction of chloroform, quaternary ammonium salt and sodium hydroxide at the interface between organic and aqueous phases. In this work, reaction conditions to generate a high concentration of dichlorocarbene in such a way to obtain a high yield of dichlorocyclopropane, were investigated. Kinetics of the reaction in synthesizing dichlorocyclopropane, such as agitation speed, quaternary ammonium salts, amount of catalyst, concentration of allyl phenyl ether, temperature, amount of chloroform and amount of sodium hydroxide were investigated in detail.

2. Experimental

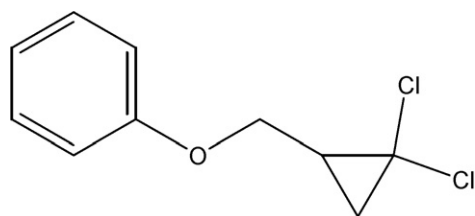
2.1. General

¹H NMR (400 MHz) and ¹³C NMR (100 MHz) were recorded on a BRUKER-AM-400 NMR spectrometer with TMS as an internal standard. The infrared spectra were measured on a Shimadzu FTIR-8700 spectrometer. Gas chromatography (GC) was carried out using a Shimadzu GC-17A instrument.

2.2. Materials

All reagents, including allyl phenyl ether, chloroform, tetraethylammonium bromide (TEAB), BTEAB, tetrabutylam-

* Corresponding author. Tel.: +91 44 27268824; fax: +91 44 27268824.
E-mail address: vrshobana01@yahoo.co.in (V. Rajendran).



(2,2-Dichloro-cyclopropylmethoxy)-benzene

Scheme 1. The structure of (2,2-dichloro-cyclopropylm ethoxy)-benzene.

monium bromide (TBAB), tetrahexylammonium bromide (THAB), tetraoctylammonium bromide, sodium hydroxide and other reagents for synthesis were guaranteed grade (GR) chemicals.

2.3. Kinetic measurements

The kinetic experiments were performed in an ordinary smooth-wall 150 ml three-necked Pyrex flask fitted with a flat-bladed stirring paddle and reflux condenser. A known quantity of NaOH (30 g) was dissolved in deionized water (30 ml, 30 wt%) to prepare an alkaline solution. Known quantities of allyl phenyl ether (4.5 mmol), BTEAB (1 mmol), nonane (internal standard 2.3 mmol), were then dissolved in chloroform (35 ml) to form the organic solution. To start the reaction, the aqueous and organic solutions were mixed in a 150-ml flask immersed in an isothermal water bath (35 °C). The sample (0.5 ml) was withdrawn periodically from the reactor and put into the glass vials containing 3 ml of dichloromethane. The contents were analysed by GC. The analysis conditions were Shimadzu GC17A, J & W Scientific Inc., capillary column (db-1 column), 100% poly(dimethyl siloxane) stationary phase, 15 m × 0.525 m column dimension, carrier gas: nitrogen (60 ml/min), FID detector, 250 °C injection temperature. The reaction was followed by estimating the disappearance of allyl phenyl ether. The pseudo-first-order rate constants were evaluated from the plot of $-\ln(k_{app})$ against time.

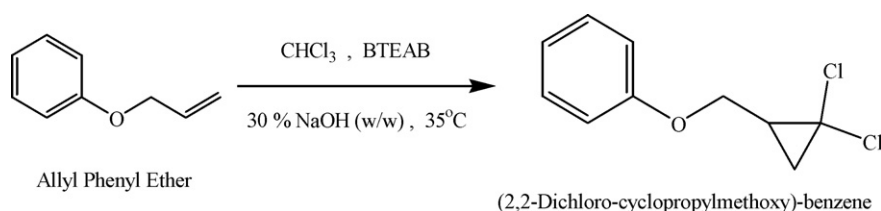
2.4. Spectral data of (2,2-dichloro-cyclopropylmethoxy)-benzene [C₁₀H₁₀OCl₂]

The following spectral data are evidence for **Scheme 1**.

¹H NMR (400 MHz, CDCl₃): δ = 7.328–6.923 (m, 5H, Aromatic), 4.307–3.926 (d, 2H, –CH₂), 2.176–2.096 (m, 1H, –CH), 1.744–1.326 (t, 2H, –CH₂); ¹³C NMR: δ = 158.368, 129.485, 121.207, 114.746, 76.975, 59.439 (CCl₂), 29.244, 25.126; MS (*m/z*): 216 (M⁺), 218 (M+2), 123, 94 (100%), 87, 77, 65, 51; ν_{max}/cm⁻¹: 3062, 3041, 2928, 1600, 1496, 1465, 1335, 1174, 1115, 883, 753.

3. Results and discussion

The kinetic experiments (followed by GC) of the dichlorocarbene addition to allyl phenyl ether were carried out under pseudo-first-order conditions, taking chloroform and 30% aqueous NaOH in excess, at 35 °C (**Scheme 2**).



Scheme 2. Formation of (2,2-dichloro-cyclopropylm ethoxy)-benzene from allyl phenyl ether.

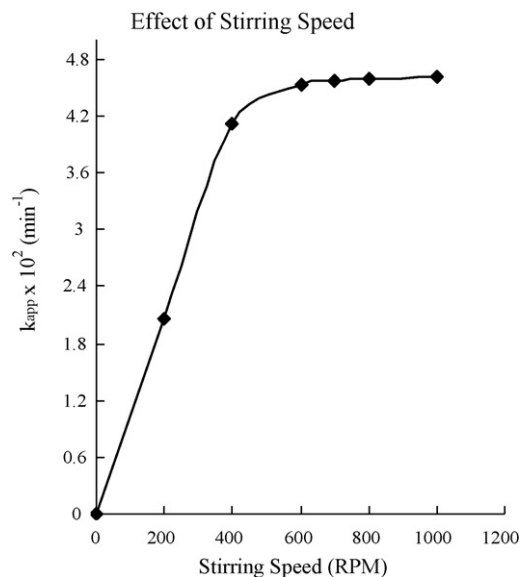


Fig. 1. Effect of the agitation speed on the apparent rate constants: 4.47 mmol of allyl phenyl ether, 22.18 mol% of BTEAB, 35 ml of chloroform, 2.34 mmol of internal standard (nonane), 30 wt% of NaOH and 35 °C.

3.1. Effect of varying stirring speed

The effect of varying the stirring speed on the rate of dichlorocarbene addition to allyl phenyl ether reaction using BTEAB was studied in the range of 0–1000 rpm. The rate of the reaction increases with increasing stirring speed. The effect of varying the stirring speed is well documented [3,10,13,22] for interfacial mechanisms which are transfer rate limited (the rate constant increases with stirring) below a given stirring speed (700–1000 rpm) and intrinsic reaction rate limited (the rate constant is nearly a constant) above this stirring speed. Similar behaviour is displayed by reactions with a real “phase-transfer” (Starks’ extraction mechanism) but with a much smaller limit of stirring speed between physical and chemical control (200–600 rpm). Thus the observed rate constants are strongly mass transfer dependent and the kinetics of the reaction is independent of the mass transfer-limited domain. The rate constants of the reaction increase as stirring speed increases and levels off to a constant value above the optimum stirring speed (700 rpm). Therefore **Fig. 1** is indicative of an interfacial mechanism not of a real “phase-transfer” mechanism. In a generally accepted PTC, irrespective of the mechanism (interfacial or real “phase-transfer”), the reaction rate constant becomes dependent on the stirring speed only below a given limit of stirring speed, the value of which depends on the nature of the mechanism.

3.2. Effect of catalyst amount

The effect of varying catalyst amount was studied in the range of 8.22–30.41 mol% of the PT catalyst (based on the substrate amount). Control experiments, in the absence of PTC were carried out and

Table 1
Effect of variation of catalyst amount^a

Catalyst (g)	$k_{app} (\times 10^2 \text{ min}^{-1})$
0.10	1.68
0.15	2.56
0.20	3.47
0.27	4.56
0.32	5.62
0.37	6.43

^a Reaction conditions: 4.47 mmol of allyl phenyl ether, 35 ml of chloroform, 2.34 mmol of internal standard (nonane), 30 wt% of NaOH, 700 rpm and 35 °C.

these showed absolutely no conversion of products, even after 4 h of stirring. This gives evidence that there is no scope for autocatalysis in the absence of the phase-transfer catalyst. The increased rates are due to the increase in the number of catalytic active sites (Table 1). The linear dependence of the rate constant on catalyst concentration shows that the reaction is believed to proceed through the abstraction mechanism. A bilogarithmic plot of the reaction rate against the catalyst concentration gives a straight line over a wide range of catalyst concentrations, having a slope 1.12. This suggests that the chemical reaction between the ion-pair and the substrate is the sole rate-determining step.

3.3. Effect of varying substrate amount

Kinetic experiments were performed by varying the substrate amount ranging from 1.49 to 14.91 mmol, maintaining other reactants such as chloroform, and 30 wt% NaOH in excess. Pseudo-first-order rate constants are obtained from the linear plots of $-\ln(k_{app})$ against time. The observed k_{app} value decreases as the substrate concentration increases (Table 2). The molar ratio of substrate to catalyst increases considerably for small increments in substrate amounts. The decrease in rate constant may be attributed to a decrease in the ratio of the number of catalytic active sites to the corresponding amount of substrate present.

3.4. Effect of NaOH concentration

The reaction rates were measured in the range of 8.93–19.64 M (25–55 g). The k_{app} values of dichlorocyclopropanation strongly depend on the concentration of sodium hydroxide [23]. The k_{app} constants were found to increase with an increase in sodium hydroxide concentration (Fig. 2). This may be attributed to the fact that hydroxide ions are less solvated by water molecules and thereby the activity of the hydroxide ion increases [24]. It is interesting to note that the conversion decreased conspicuously after adding 50 g of sodium hydroxide. It is because the solution was saturated by the addition of 50 g of sodium hydroxide and 4.47 mmol of allyl phenyl ether to 30 ml of water, leading to the salting out of allyl phenyl ether as a black gel. Under this circumstance, the dichlorocyclopropanation system would be changing from a liquid–liquid PTC to a liquid–solid (NaOH) PTC. The change would decrease the

Table 2
Effect of variation of substrate amount^b

Entry	Substrate amount (mmol)	Substrate/catalyst	$k_{app} (\times 10^2 \text{ min}^{-1})$
1	1.49	5.52	5.53
2	2.98	11.04	5.04
3	4.47	16.56	4.56
4	7.45	27.59	3.67
5	11.18	41.41	2.54
6	14.91	55.22	1.23

^b Reaction conditions: 22.18 mol% of BTEAB, 35 ml of chloroform, 2.34 mmol of internal standard (nonane), 30 wt% of NaOH, 700 rpm and 35 °C.

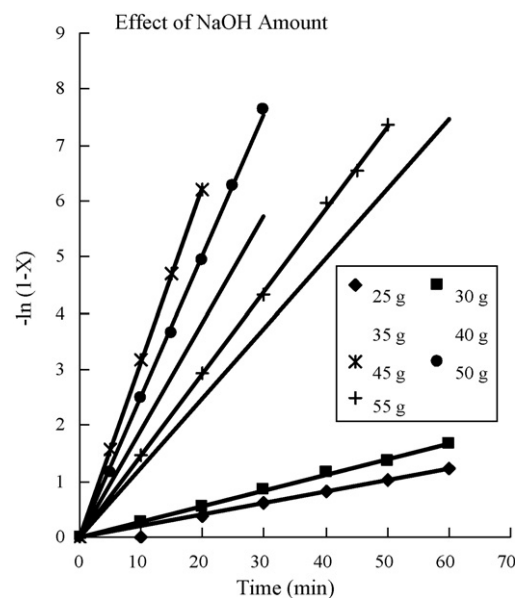


Fig. 2. Effect of the amount of NaOH on the conversion of allyl phenyl ether: 4.47 mmol of allyl phenyl ether, 22.18 mol% of BTEAB, 35 ml of chloroform, 2.34 mmol of internal standard (nonane), 700 rpm and 35 °C.

reaction rate sharply. As shown in Fig. 3, the conversion is first increased with an increase in the amount of NaOH up to 45 g and then decreased with any further increase in the amount of NaOH.

3.5. Effect of quaternary ammonium salts

Quaternary ammonium salts are generally used as phase-transfer catalysts to promote reaction rate. In addition to BTEAB, four other quaternary ammonium salts, such as TEAB, TBAB, THAB and tetraoctylammonium bromide (TOAB), were investigated to test their reactivities. The experimental results are listed in Table 3. The observed k_{app} value increases with increasing the number of carbon atoms present in the ammonium cation (Q^+) [1]. Based on

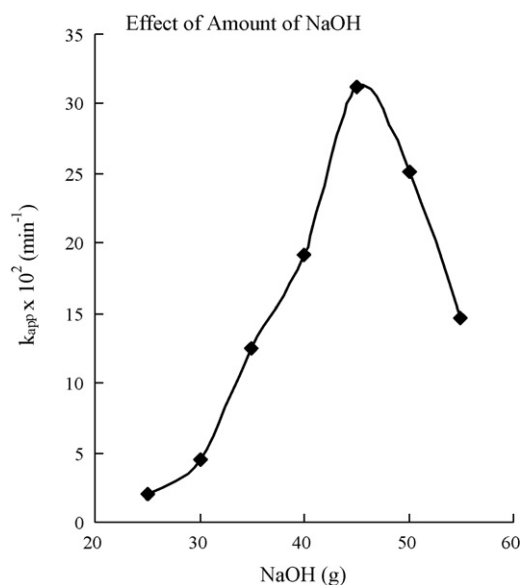


Fig. 3. Effect of the amount of NaOH on the apparent rate constant, k_{app} : same reaction conditions as given in Fig. 2.

Table 3
Effects of the phase-transfer catalysts on the apparent rate constant (k_{app})^c

Catalyst	$k_{app}(\times 10^2 \text{ min}^{-1})$
TEAB	3.42
BTEAB	4.56
TBAB	5.75
THAB	7.86
TOAB	9.74

^c Reaction conditions: 4.47 mmol of allyl phenyl ether, 22.18 mol% of PTCs, 35 ml of chloroform, 2.34 mmol of internal standard (nonane), 30 wt% of NaOH, 700 rpm and 35 °C.

the experimental results, the order of the reactivities of these quaternary ammonium salts are: TOAB > THAB > TBAB > BTEAB > TEAB.

3.6. Effect of the amount of chloroform

In this work, chloroform acts both as organic solvent and one of the organic reactants. The effect of the amount of chloroform on the conversion of allyl phenyl ether is shown in Table 4. The conversion is reduced with the increase in the amount of chloroform. In principle, the generation of dichlorocarbene, which is favorable to enhance the reaction, is increased with the increase in the amount of chloroform. However, the generation of dichlorocarbene occurs at the interface of the two phases. The interfacial area remains at a constant value for a constant agitation speed. Furthermore, the generation of dichlorocarbene is also limited due to the limited amount of phase-transfer catalyst added and the amount of water. The dichlorocarbene generated is diluted by increasing the amount of chloroform in the organic phase. Thus, the concentration of dichlorocarbene in the organic phase (chloroform) is decreased with the increase in the amount of chloroform. In this way, the conversion is decreased by increasing in the amount of chloroform.

3.7. Influence of temperature

The effect of varying temperature on the rate of dichlorocyclopropanation to allyl phenyl ether was studied in the temperature range of 303–318 K. The kinetic profile of the reaction is obtained by plotting $-\ln(1-X)$ versus time (Fig. 4). The rate constants increase with the increase in temperature. The energy of activation is calculated from an Arrhenius plot, $E_a = 13.99 \text{ kcal mol}^{-1}$ (Fig. 5). The activation energy of intraparticle diffusion of anion exchange resins in aqueous solutions is of the order of 5–10 kcal mol⁻¹ [25]. The activation energy for the dehydrobromination of (2-bromoethyl)benzene in the presence of TOAB was reported to be 8 kcal mol⁻¹ and for this an extraction mechanism was proposed [26].

A higher E_a value suggests that a contribution of intrinsic reactivity limitations is more than that of intraparticle diffusion limitations. A higher E_a value has been reported [27] for the polystyrene bound trimethylammonium ion catalysed reaction, which was controlled by strict intrinsic reactivity under triphase conditions. The activation energy for the heterogeneous ethylation

Table 4
Effect of the amount of chloroform on the apparent rate constant (k_{app})^d

CHCl ₃ (ml)	$k_{app}(\times 10^2 \text{ min}^{-1})$
25	6.07
35	4.56
45	3.72
55	2.67
65	1.22

^d Reaction conditions: 4.47 mmol of allyl phenyl ether, 22.18 mol% of BTEAB, 2.34 mmol of internal standard (nonane), 30 wt% of NaOH, 700 rpm and 35 °C.

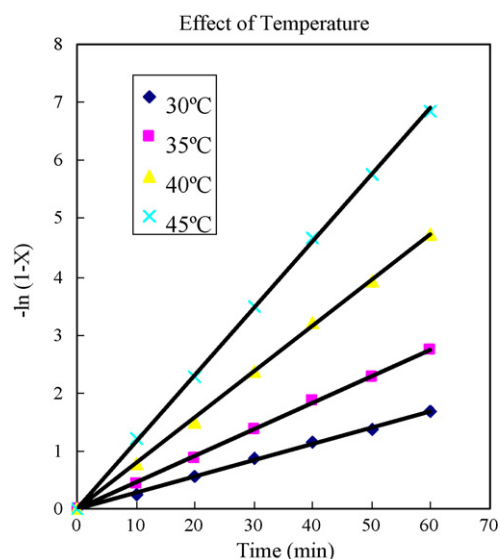


Fig. 4. Effect of the temperature on the conversion of allyl phenyl ether: 4.47 mmol of allyl phenyl ether, 22.18 mol% of BTEAB, 35 ml of chloroform, 2.34 mmol of internal standard (nonane), 30 wt% of NaOH and 700 rpm.

of phenylacetonitrile was reported to be 20 kcal mol⁻¹ and for this an interfacial mechanism was proposed [28]. The observed energy of activation for dichlorocarbene addition to allyl phenyl ether is 18.99 kcal mol⁻¹ and hence we concluded, that intrinsic reactivity is the rate-limiting step since the intraparticle diffusion is minimized at 700 rpm.

3.8. Mechanism

From the observed experimental results, it is clear that the dependence of the kinetic data on the entire stirring speed range, concentration of the catalyst, aqueous hydroxide ions, temperature and higher E_a value are consistent with the interfacial mechanism.

The generation and reaction of carbene with allyl phenyl ether may be represented in Scheme 3.

According to Starks' extraction mechanism [1], it was thought that the hydroxide ion may be extracted from an aqueous

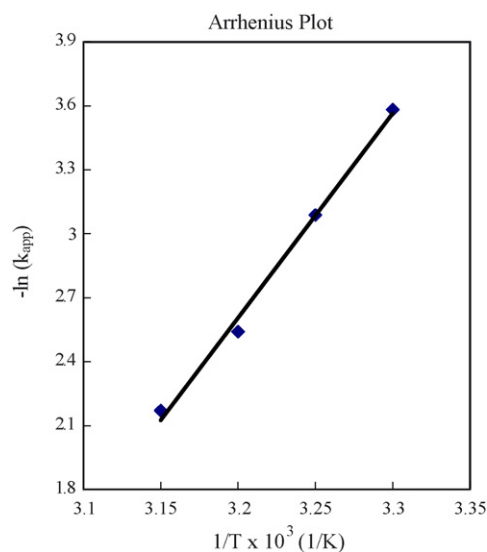
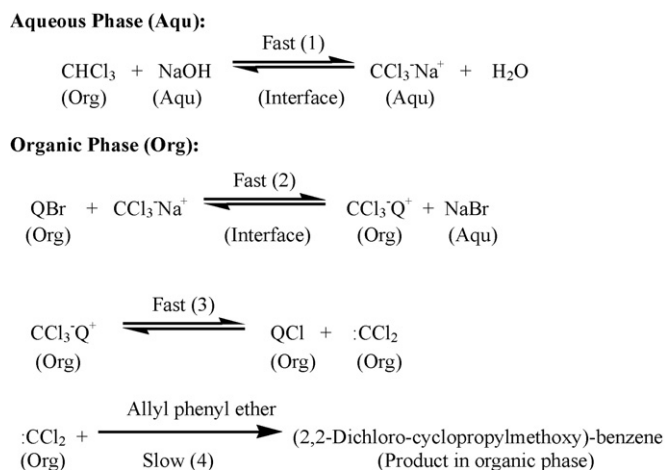


Fig. 5. Arrhenius plot: dependence of k_{app} on temperature; same reaction conditions as given in Fig. 4.



Scheme 3. Mechanism for the dichlorocarbene addition to allyl phenyl ether under PTC conditions.

reservoir into an organic phase with the help of quaternary ammonium cations. Makosza and Bialecka [29] proposed an alternative mechanism for dichlorocarbene addition reactions in which deprotonation of the organic substrate by the hydroxide ion occurs at the interface. According to this mechanism, the role of catalyst is to remove the resulting organic anion from the interface into the bulk organic phase for subsequent reaction. Several studies [28,30] have provided support for various aspects of Makosza's mechanism.

It has been established by Makosza and Fedorynski [31] that the slowest reaction is the addition of CCl_2 (dichlorocarbene) to alkenes, considering the other steps as fast equilibrium processes. In our study, a fractional order with respect to catalyst concentration suggests that the step (2) is not the sole rate-determining one and that of the chemical reaction in the organic phase is also rate-determining. The effects of other experimental results such as stirring speed, sodium hydroxide concentration and temperature over the observed rate of the reaction support the interfacial mechanism proposed by Makosza for the PTC/ OH^- systems rather than Starks' extraction mechanism.

4. Conclusion

In conclusion, the reaction rate of dichlorocarbene addition to allyl phenyl ether was investigated under phase-transfer catalysts condition. The factors affecting the overall reaction rate, such as stirring speed, volume of chloroform, amount of catalyst, amount

of sodium hydroxide, amount of substrate and temperature were studied to determine the optimal operating conditions. The reaction was not affected by stirring speeds higher than 700 rpm. The apparent reaction rates were observed to obey the pseudo-first-order kinetics with respect to the organic reactant. The reaction rate increased with increasing temperature and catalyst amount. The apparent activation energy for this two-phase reaction was determined to be $13.99 \text{ kcal mol}^{-1}$.

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