Kinetic Study on Exchange Reaction of Alkyl Halides under Gas–Liquid Phase-transfer Catalysis Conditions

Pietro Tundo *
Istituto di Chimica Industriale dell'Università di Messina, Casella Postale 29, 98010 S. Agata di Messina, Italy
Francesco Trotta and Giovanni Moraglio
Istituto di Chimica Macromolecolare dell'Università di Torino, Via G. Bidone 36, 10125 Torino, Italy

Catalytic exchange of halogen in hydrocarbon halides can be performed continuously under gas–liquid phase-transfer catalysis conditions by feeding a solid bed, containing a 'onium salt as phase-transfer catalyst, with the reagents. The solid support for the catalyst plays an important part in solvating the anions and so its nature affects the activity. The best support found consisted of glass spheres. The reaction does not depend on gaseous diffusion, but does require diffusion of the reagents into the catalyst liquid film. To obtain kinetic constants, experimental conversion curves were correlated with empirically calculated formulae.

Gas–liquid phase-transfer catalysis (g.l.–p.t.c.), a development of phase-transfer catalysis,[1] allows activated anions to react under continuous-flow conditions and in the gas phase in processes widely used in industry. In g.l.–p.t.c.[2] the anions are in the liquid film constituted by the molten p.t. catalyst, which is supported over an inorganic, 'inactive' solid bed. Over this film the gaseous reagents and the products continuously and reversibly diffuse, react, and leave the solid bed. By working under g.l.–p.t.c. conditions several syntheses have been already achieved, *e.g.* alkylation of phenols,[3] thiols,[3] and carboxylates,[4] alkylation of malonic esters,[5] selective mono-*N*-alkylation of aromatic amines,[6] transformation of primary alcohols into the corresponding halides,[7] transesterification,[8] *etc.*

In these previous papers[9] we inferred that the reaction develops first through adsorption of the reagent on the liquid film; the reagent then reacts with activated anion and then the product is desorbed from the catalytic bed. The adsorption and desorption are obviously reversible phenomena which may be controlled by diffusion; in our case, depending on the reaction rate, the innermost layer of liquid film may be not as effective a catalyst as the outer one. This situation is typical of catalysis by porous solids coated with a liquid catalyst,[10a] (supported liquid-phase catalysis: s.l.p.c.);[10b] but in our case, unusually, the catalyst is an organic liquid film which promotes anion activation. Another parallel could be made with gas-liquid chromatography (g.l.c.), but here the liquid film promotes separation whilst in g.l.–p.t.c. it facilitates reactions.

For further and more appropriate applications of this method it is necessary to know the most important parameters that govern the reaction; with this in mind we report here some preliminary results for the halogen-exchange reaction (1)

$$\mathrm{Bu^nBr + Pr^nCl \xrightleftharpoons{Bu_4P^+(Cl^-,Br^-)} Bu^nCl + Pr^nBr} \quad (1)$$

between 1-bromobutane and 1-chloropropane promoted by the tetra-n-butylphosphonium phase-transfer catalyst and carried out under various conditions of temperature, flow, and amount and type of catalytic support. The onium salt is liquid at the temperature employed ($Bu_4P^+Cl^-$ m.p. 65 °C; $Bu_4P^+Br^-$ m.p. 88 °C). Halogen exchange in hydrocarbon halides has been reported under g.l.–p.t.c. conditions;[11] it proceeds indefinitely. Reaction (1) is especially simple, and can be easily carried out at atmospheric pressure and followed by g.l.c.; moreover its rate depends on anionic activation of Br^- and Cl^-, their nucleophilicity being a function of the reaction environment.

There is little doubt that reaction (1) proceeds through the steps shown in Scheme 1; equations (2), (4), (5), and (7) may depend on diffusion; equations (3) and (6) are the chemical reactions. To evaluate the relative importance of the equilibria (2)—(7), it is necessary to work in simple, clean conditions and primarily to avoid any possible interference with the supporting solid.

$$\mathrm{PrCl_{gas} + Q^+Br^-{}_{liq} \rightleftharpoons (PrCl + Q^+Br^-)_{liq}} \quad (2)$$

$$\mathrm{(PrCl + Q^+Br^-)_{liq} \underset{k_2}{\overset{k_1}{\rightleftharpoons}} (PrBr + Q^+Cl^-)_{liq}} \quad (3)$$

$$\mathrm{(PrBr + Q^+Cl^-)_{liq} \rightleftharpoons PrBr_{gas} + Q^+Cl^-{}_{liq}} \quad (4)$$

$$\mathrm{BuBr_{gas} + Q^+Cl^-{}_{liq} \rightleftharpoons (BuBr + Q^+Cl^-)_{liq}} \quad (5)$$

$$\mathrm{(BuBr + Q^+Cl^-)_{liq} \underset{k_4}{\overset{k_3}{\rightleftharpoons}} (BuCl + Q^+Br^-)_{liq}} \quad (6)$$

$$\mathrm{(BuCl + Q^+Br^-)_{liq} \rightleftharpoons BuCl_{gas} + Q^+Br^-{}_{liq}} \quad (7)$$

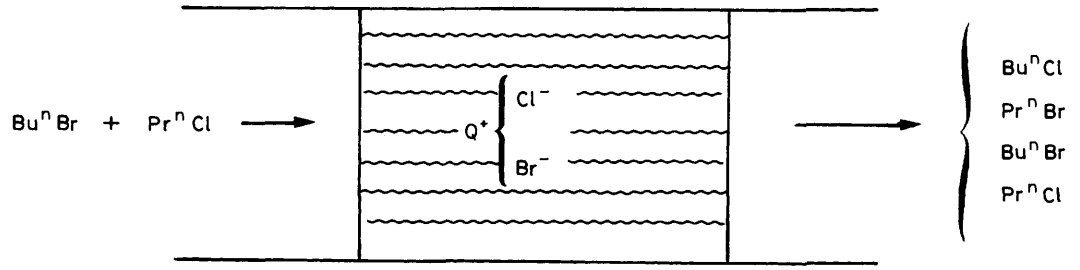
Scheme 1. Reactions and equilibria involved in halogen exchange (Q^+ is the quaternary 'onium salt)

Experimental

1-Bromobutane, 1-bromopropane, 1-chlorobutane, and 1-chloropropane were commercial samples and used without further purification. Tetra-n-butylphosphonium bromide was synthesized according to the literature method.[12] Inorganic supports employed were: silica gel (Merck no. 7734 70—230 mesh), zeolites of 1.0 nm cavity (Merck no. 5703, 2 mm diam.), α-alumina (spheres 3 mm in diam), and glass spheres (0.10 mm diam.; density 2.72 g cm^{-3}).

Catalytic beds were made by dissolving the required amount of 'onium salt in dichloromethane and adding the solid inorganic support; the solvent was then removed by rotary evaporator under vacuum, and the solid put in an oven at 120 °C for 2 h. The catalytic bed was put into a thermostatically controlled glass column (30.0 cm length, 0.5 cm diam.) to perform the reactions (Scheme 2). The length of the catalytic bed in the column varied from 1.0 to 28.0 cm.

The liquid reagent mixture was passed continuously into the column with a syringe pump (Sage Instruments 314A). All the reagents and products are in the gas phase in the column at atmospheric pressure and at working temperatures (1-bromobutane, 1-bromopropane, 1-chlorobutane, and 1-chloropropane, b.p.s 101.6, 78.4, 71.0, and 46.6 °C, respectively). After leaving the reactor the reaction mixture was collected by condensation; it was analysed by g.l.c. (Varian Vista 6000 instrument). At the beginning the reactor effluent is richer in the



Scheme 2. G.l.–p.t.c. halogen exchange

most volatile compounds; steady conditions are reached later. Meanwhile, the 'onium salt counteranion reaches a constant $Cl^-:Br^-$ ratio in the bed. To give a simple computation formula, the initial 1-bromobutane:1-chloropropane molar ratio was 1.0:1. Reaction conversions are then given by equation (8), where A refers to the peak areas corresponding to the reaction components measured by g.l.c., and f is the corresponding normalization factor.

$$\text{Conversion} = \frac{(Af)_{\mathrm{BuCl}} + (Af)_{\mathrm{PrBr}}}{(Af)_{\mathrm{BuCl}} + (Af)_{\mathrm{PrBr}} + (Af)_{\mathrm{BuBr}} + (Af)_{\mathrm{PrCl}}} \quad (8)$$

Results and Discussion

A few runs were carried out to evaluate the influence of the support on the reaction rate: as solid matrices glass spheres, α-alumina spheres, zeolites, and silica gel were used. The results are reported in the Table. A correlation seems to exist between the activity of the bed (% conversion) and the $Cl^-:Br^-$ ratio in the bed at the steady state: the lower the $Cl^-:Br^-$ ratio, the higher the conversion. This implies, moreover, that Cl^- reactivity is higher than that of Br^-.*

It is well known in p.t.c. that solvation influences the reactivity of Cl^- to a greater extent than Br^-; in particular, the reaction rate for both anions becomes higher with decreasing anion stabilization: it has been reported[13] that when the reaction rate is low (if water solvates the anion), the activity of Br^- is higher than that of Cl^-; conversely, in the absence of protic interactions the reaction rate is very high and the anion reactivities are reversed. This phenomenon also occurs in our case, where the reactivity of Cl^- is always greater than that of Br^-: the Table shows that the $Cl^-:Br^-$ ratio is less than unity for all supports tested. Moreover, the anion solvation provided by the support is variable, being higher for zeolites and silica gel. This behaviour is in accord with the presence on these supports of bonded water and/or a higher concentration of surface OH groups, which change the reaction microenvironment by solvating the anions.[14]

From the results in the Table it is possible to infer that only glass spheres and α-alumina behave as really inactive supports, since they show higher activity. Consequently, as a solid support to carry out further experiments, glass spheres were selected; furthermore they have more easy measurable and constant surface properties than α-alumina. Some aspects of the phenomenological behaviour of reaction (1) determined by continuous-flow reactor under g.l.–p.t.c. conditions are now described.

Different amounts of p.t. catalyst were put on the glass spheres, varying from 0.5 to 10 wt %; the liquid film thickness then varied from 0.26 to 4.60 μm, respectively.

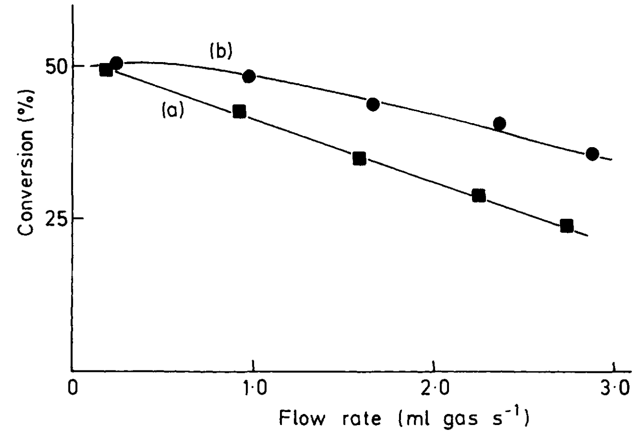


Figure 1. Influence of reagent flow at two temperatures: (a) 120 °C; (b) 140 °C. The reagent flow was measured in the liquid state and transformed to gaseous by application of the ideal gas law. The pressure was atmospheric; 9.0 g of glass spheres (0.1 mm diam.) were coated with 10 wt % of tetra-n-butylphosphonium bromide. Conversions were derived by equation (8)

Table. Influence of different supports on the g.l.–p.t.c. reaction[a]

Solid bed	$Cl^-:Br^{-\,b,c}$	Conversion (%)[c]
Glass spheres	0.052:1	20
α-Al_2O_3 spheres	0.067:1	17
Zeolites	0.860:1	8.5
Silica gel	0.230:1	10

[a] Support (1.6 g) coated with $Bu_4P^+Br^-$ (10 wt %); T 140 °C; liquid flow rate 12 ml h^{-1}. [b] The reaction was interrupted and after cooling (about 2 h) a fraction of the bed was titrated potentiometrically with a 0.1M solution of $AgNO_3$. [c] Determinated after 2 h, at steady state.

Figure 1 shows conversion as a function of flow rate (F = ml of gaseous reactants per second), with a 1:1 molar mixture of 1-bromobutane and 1-chloropropane, at 120 and at 140 °C. At the same flow rate, the lower the temperature the lower the conversion, but both the curves at zero flow (infinite reaction time) approach closely to 50%: this means that thermodynamic equilibrium has been reached and that the equilibrium constant of reaction (1) is unity.† These results were also consistent with free energy and enthalpy calculations obtained by group contribution methods.[15]

---

* The relevant equations are reported in Supplementary Publication No. SUP 56714 (3 pp.). For details of Supplementary Publications see Instructions for Authors (Issue no. 1, 1988).

† $(k_1/k_2)(k_3/k_4) = 1$. Intuitively, we would expect bond energies in RCH_2–Hal not to depend on the length of the alkyl chain. Moreover, both reaction (1) and its reverse (feeding the reactor with Bu^nCl and Pr^nBr), carried out under the same conditions and at different temperatures, show a similar trend (conversion and reaction composition at thermodynamic equilibrium).

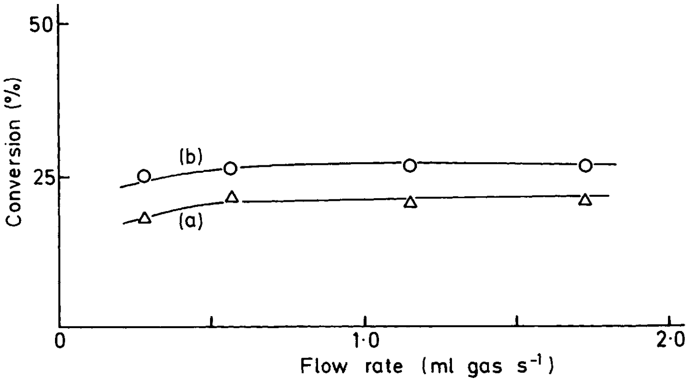


Figure 2. Influence of gaseous diffusion on two different catalytic beds: (a) 2.5 wt % of $Bu_4P^+Br^-$; (b) 5 wt % of $Bu_4P^+Br^-$; *V*/*F* ratio always constant; *T* 140 °C; other conditions as Figure 1

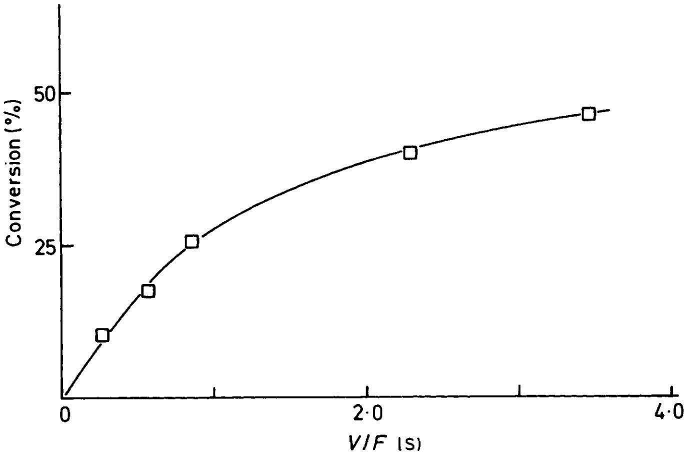


Figure 3. Influence of *V*/*F*; catalytic bed: 1.6 g of glass spheres coated with 10 wt % of $Bu_4P^+Br^-$; other conditions as Figure 1. The curve is calculated according to equation (9)

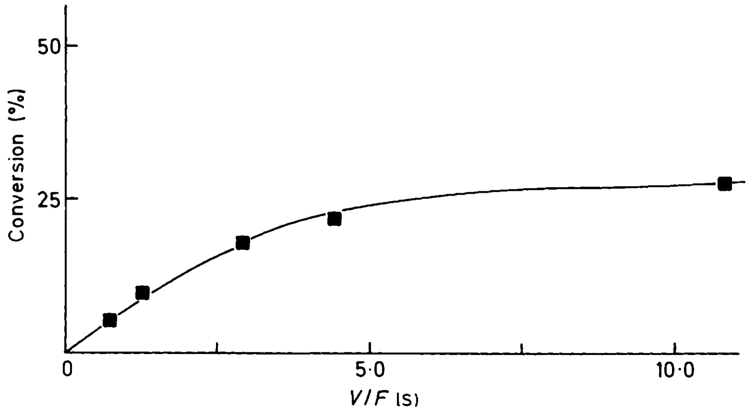


Figure 4. Influence of *V*/*F*; reaction conditions as Figure 3, but reagent mixture of different composition: BuBr:PrCl:cyclohexane (2.2:1.8:16.0 v/v/v). The curve is calculated according to equation (10)

Figure 2 shows four experiments at constant *V*/*F* ratio (*V* = volume of the catalytic bed). These were carried out by changing *V* and *F* simultaneously and proportionally in order to keep *V*/*F* constant. It is known that *V*/*F* in continuous systems corresponds to the time for reactions carried out in batch reactors. It appears that only if *F* is lower than 0.50 ml s^{-1} is the rate of reaction not constant; thus it is influenced by the diffusion of reactants in the gaseous phase. For *F* higher than 0.50 ml s^{-1} the gaseous diffusion rate is not a rate-controlling step of the reaction: therefore all the subsequent runs were carried out at a gaseous flow rate higher than 0.50 ml s^{-1}. In Figures 3 and 4 two series of experiments are plotted as conversions *vs.* *V*/*F*; both series were carried out at 140 °C, with a reagent molar ratio of 1:1 and at atmospheric pressure.

For Figure 3 the reaction (1) was performed without solvent, whereas the data of Figure 4 were obtained with the reagents

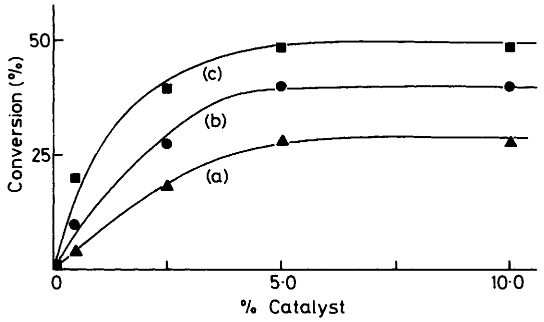


Figure 5. Influence of catalyst % at three different temperatures: (a) 120 °C; (b) 140 °C; (c) 160 °C; other conditions as Figure 1

diluted in cyclohexane. This compound could be regarded as an inert component, being merely a gas carrier; its physical effect is to lower the reagents' partial pressure (to a theoretical 0.216 atm, by ideal gas law). Nevertheless, it might also intervene chemically in the reaction. The experimental data of Figures 3 and 4, elaborated by the method of finite differences, fit well the empirical relationships (9) and (10), where X is the conversion

$$X = 0.411\,(1 - e^{-\tau/1.30}) \qquad (9)$$

(reagents 1:1 molar at 1 atm)

$$X = 0.306\,(1 - e^{-\tau/3.15}) \qquad (10)$$

(reagents 1:1 molar at 0.216 atm)

and τ is V/F. The curves in Figures 3 and 4 follow equations (9) and (10), respectively. From (9) and (10) we can calculate and therefore evaluate the initial rates of reaction (theoretically in the absence of products) at the two different concentrations of reagents. From these computations an overall order of two can be attributed to reaction (1).

Further calculations on the initial rate by the same procedure, but on reactions carried out in non-stoicheiometric ratio ($Bu^nBr:Pr^nCl$ 0.1:1 and 10.0:1) confirmed this overall order, and indicated apparent orders of 1.40 and 0.60 with respect to Pr^nCl and Bu^nBr, respectively. In other words, the kinetic behaviour of the reaction is mainly determined by the concentration of Pr^nCl; this result agrees with the data in the Table, since reaction with Br^- controls the overall reaction rate.

Moreover, comparison between Figures 3 and 4 leads to an important consideration: while in the absence of cyclohexane the reaction reaches its highest possible conversion at a V/F value of about 4 s, in the presence of cyclohexane a similar time is required but the conversion is only 25%. Because the time spent by the reagents in the reactor is the same in both cases, this behaviour might mean either of two things: (i) the reaction is controlled by liquid diffusion since the conversion, beyond a given point, does not increase comparably with the time spent by the reagent in the reactor (see also Figure 5); (ii) in spite of its non-polarity, which should improve anion activity, cyclohexane plays an unfavourable role in the reaction, maybe by excluding the reagents from the liquid phase of the catalyst by adsorption in their place.

Liquid diffusion processes clearly play an important role in Figure 5, which shows conversion *vs.* % of Bu_4P^+ used. Different initial rates of conversion correspond to different temperatures used. This is reasonable, but the subsequent different asymptotes can be attributed only to a slow diffusion process that occurs in the inner catalyst layers.

Conclusions

Under either liquid–liquid– or gas–liquid–p.t.c. conditions, the best solvent or support for carrying out displacement reactions must provide as little polar interaction as possible with the nucleophile.

The catalytic liquid phase of the 'onium salt that operates in g.l.–p.t.c. is able to provide high activation, so that thermodynamic equilibrium in halide-exchange reactions is easily reached. This is due not only to the relatively high temperatures used, but also to the particular activating nature of the unusual liquid phase in which the reaction occurs.

In g.l.–p.t.c. over a bed of glass spheres coated with 10 wt % tetra-n-butylphosphonium halide, the organic exchange reaction does not depend on gaseous diffusion (gaseous flow >0.50 ml s^{-1}), but is strongly affected by diffusion of gaseous reagents into the liquid catalyst.

These facts define a close connection between g.l.–p.t.c. and other well known industrial processes operating under s.l.p.c. and continuous-flow conditions (*e.g.* $SO_2 \longrightarrow SO_3$ oxidation, alkylation of aromatic substrates, oxychlorination, *etc.*).

Acknowledgements

This work was realized with grants from the Ministero Pubblica Istruzione, Rome.

References

1 (*a*) W. P. Weber and G. W. Gokel, in 'Phase Transfer Catalysis in Organic Synthesis,' Springer-Verlag, West Berlin, 1977; (*b*) C. M. Starks and C. Liotta, in 'Phase Transfer Catalysis,' Academic Press, New York, 1978; (*c*) E. V. Dehmlow and S. S. Dehmlow, in 'Phase Transfer Catalysis,' Verlag Chemie, Weinheim, 1980; (*d*) F. Montanari, D. Landini, and F. Rolla, *Top. Curr. Chem.*, 1981, **101**, 147.

2 P. Tundo, *J. Org. Chem.*, 1979, **44**, 2048.

3 E. Angeletti, P. Tundo, and P. Venturello, *J. Chem. Soc., Perkin Trans. 1*, 1982, 1137.

4 E. Angeletti, P. Tundo, and P. Venturello, *J. Chem. Soc., Perkin Trans. 1*, 1982, 993.

5 (*a*) E. Angeletti, P. Tundo, and P. Venturello, It. Pat. Appl. 23669 A/82; (*b*) E. Angeletti, P. Tundo, and P. Venturello, *J. Chem. Soc., Perkin Trans. 1*, 1987, 2159.

6 (*a*) F. Trotta and P. Tundo, It. Pat. Appl. 21568 A/86; (*b*) G. Moraglio, F. Trotta, and P. Tundo, *J. Org. Chem.*, 1987, **52**, 1300.

7 (*a*) E. Angeletti, P. Tundo, and P. Venturello, It. Pat. 22902 A/82; (*b*) E. Angeletti, P. Tundo, and P. Venturello, *J. Chem. Soc., Perkin Trans. 1*, 1987, 2157.

8 E. Angeletti, P. Tundo, and P. Venturello, *J. Org. Chem.*, 1983, **48**, 4106.

9 P. Tundo, P. Venturello, and E. Angeletti, *J. Chem. Soc., Perkin Trans. 2*, 1983, 485.

10 (*a*) J. Villadsen and H. Livbjerg, *Catal. Rev.-Sci. Eng.*, 1978, **17**, 203; (*b*) P. R. Roney, *Chem. Eng. Sci.*, 1968, **23**, 1021.

11 P. Tundo, P. Venturello, and E. Angeletti, *J. Chem. Soc., Chem. Commun.*, 1980, 1127.

12 M. Grayson and P. T. Keough, *J. Am. Chem. Soc.*, 1960, **82**, 3919.

13 D. Landini, A. Maia, F. Montanari, and P. Tundo, *J. Am. Chem. Soc.*, 1979, **101**, 2526.

14 P. Tundo and P. Venturello, *J. Am. Chem. Soc.*, 1979, **101**, 6606.

15 O. A. Hougen, K. M. Watson, and R. A. Ragatz, in 'Chemical Process Principles,' part II, 2nd edn., Wiley, New York, 1959.

Received 9*th November* 1987; *Paper* 7/1975