November, 1994] © *1994 The Chemical Society of Japan* *Bull. Chem. Soc. Jpn.*, ***67***, *2949—2955(1994)* 2949

Study of the Pyridine 1-Oxide-Catalyzed Two-Phase Reversible Exchange Reaction of Benzoyl Chloride and Butanoate Ion

Maw-Ling WANG*, Chin-Chou OU, and Jing-Jer JWO†
Department of Chemical Engineering, National Tsing Hua University, Hsinchu, Taiwan 30043
†Department of Chemistry, National Cheng-Kung University, Tainan, Taiwan 70101

(Received May 16, 1994)

The reaction of benzoyl chloride (PhCOCl) and butanoate ion ($PrCOO^-$) catalyzed by pyridine 1-oxide (PNO) in the medium H_2O/CH_2Cl_2 leads to equilibrium with butanoyl chloride (PrCOCl) and benzoate ion ($PhCOO^-$) and vice versa. The rate-determining step takes place in the organic phase and PrCOCl is much more reactive than PhCOCl. The effects of chloride ion, hydroxide ion, pyridine 1-oxide, reactants and temperature on the reaction rate and the equilibrium conversion of acyl chloride (RCOCl) were investigated. Satisfactory detailed mechanistic interpretations of the kinetic results are given.

Phase-transfer catalysis (PTC) has versatile applications in organic syntheses via two-phase reactions.[1—6] PTC technique is extensively applied to various reactions, such as substitution, alkylation, and redox reactions to synthesize specialty chemicals. Normal phase-transfer catalysis (NPTC) involves continuous transport of the anion from the aqueous phase to the organic phase for reaction with the lipophilic quaternary cation.[1,3,4] In reverse phase-transfer catalysis (RPTC), the cation in the aqueous phase is transported to the organic phase for reaction with the lipophilic anion.[7—9] In contrast, in inverse phase-transfer catalysis (IPTC), the reactant in the organic phase is converted to an ionic intermediate and transported to the aqueous phase for reaction.[10—19] The IPTC technique is applied to synthesize acid anhydrides[17,18] and ketones.[19] Kuo and Jwo[18] studied the kinetics and mechanism of the IPTC reaction of PhCOCl and $PhCOO^-$ ion catalyzed by pyridine 1-oxide (PNO).

In our preliminary systematic investigation of IPTC reaction of PhCOCl and $RCOO^-$ (R=Ph, Me, Et, *i*-Pr, *n*-Bu and *n*-C_5H_{11}), the expected acid anhydrides were obtained and the limiting reactant (PhCOCl) was consumed completely. However, only about half the PhCOCl was consumed in IPTC reaction of PhCOCl and $PrCOO^-$ ion and the equilibrium concentration of PhCOCl remained constant for several hours. IPTC reaction of butanoyl chloride (PrCOCl) and benzoate ion ($PhCOO^-$) catalyzed by PNO also led to equilibrium. Therefore this reaction system can be best described by reaction (R1). It is worthwhile to study this interesting system further. We investigated the effects of chloride ion, hydroxide ion, pyridine 1-oxide (PNO), reactants, and temperature in this interesting system. The results are rationalized according to a proposed reaction scheme,

$$PhCOCl_{(org)} + PrCOO^-_{(aq)} \rightleftharpoons PrCOCl_{(org)} + PhCOO^-_{(aq)} \quad (R1)$$

Experimental

Materials: Pyridine 1-oxide (PNO, C_5H_5NO, 95%), naphthalene ($C_{10}H_8$, 99%) (Merck), benzoyl chloride (PhCOCl, extra pure) (Ferak), benzoic acid (PhCOOH, extra pure), butanoic acid (PrCOOH, extra pure) (Hanawa), sodium benzoate (PhCOONa, extra pure) (Ishizu), butanoyl chloride (PrCOCl, GR) (TCI, Tokyo) were used. Other chemicals used were of the highest reagent grade commercially available. Because of the hydroscopic property of PNO, $(PNO)H^+Cl^-$ crystals (mp 179—181 °C) were used instead. Deionized water was obtained from reverse osmosis (Millipore Milli-RO 20).

Procedures: The reactor, a three-necked Pyrex flask (250 mL), fitted with a flat-bladed stirring paddle, is submerged into a water bath in which the temperature is controlled constant within ±0.1 °C. A kinetic run was started by adding aqueous solution (50 mL, containing known amounts of PNO, PrCOOH, and NaOH) to organic phase solution (50 mL, containing known amounts of PhCOCl and $C_{10}H_8$) in the flask. Both solutions were thermostated at the desired temperature for at least 20 min. During the reaction, an aliquot (0.2 mL) was withdrawn at a chosen time and was immediately extracted with hexane (0.2 mL) and water (0.5 mL), which was shaken vigorously for 30 s. After separation of the two phases, the organic phase was further dilluted with dichloromethane and analyzed by HPLC using an internal standard.

On the HPLC (Shimadzu LC-9A, Japan), the analytical conditions were: column, Shim-pack CLC-ODS (M); eluent, $CH_3CN/H_2O=65/35$ by volume; flow rate, 1.2 mL min^{-1}; wavelength, 254 nm (UV detector); elution period (min), PhCOCl (7.00), $(PhCO)_2O$ (8.10), $C_{10}H_8$ (8.70). The response factor f was calibrated using $C_r/C_{is}=f(S_r/S_{is})$ (C_i, concentration; S, peak area; is, internal standard; r, unknown compound). The values of f measured were 0.310±0.003 for [PhCOCl]=(0.002—0.02) M and 0.167±0.003 for $[(PhCO)_2O]=(0.002—0.02)$ M with $[C_{10}H_8]=0.0200$ M (1 M=1 mol dm^{-3}). The observed pseudo-first-order rate coefficient was determined by linear least-squares fit of the plot ln [PhCOCl] vs. time.

The effect of pH on the distribution of PNO between aqueous and CH_2Cl_2 phases was tested by measuring the concentration of PNO in CH_2Cl_2 phase spectrophotometrically at 275 nm. The pH of sodium butyrate solution was adjusted by adding NaOH solution (1 M) to aqueous solution (20 mL) containing a known amount of PrCOOH and $(PNO)H^{+}Cl^{-}$.

Results and Discussion

In the reaction of PhCOCl and $PhCOO^{-}$ ion catalyzed by PNO in a H_2O/CH_2Cl_2 solution, Kuo and Jwo[18] found that the two-phase solution was mixed uniformly when the speed of agitation exceeded 1100 rpm. Resistance of mass transfer was then kept constant and the rate of reaction was unaffected by a speed of agitation greater then 1100 rpm. The reaction of PhCOCl and PNO in the organic phase to produce the intermediate $(PhCOONP^{+})$ was the rate-determining step. In this work, the reaction of PhCOCl and $PrCOO^{-}$ ion catalyzed by PNO in a H_2O/CH_2Cl_2 medium was examined at 1200 rpm. The conversion of PhCOCl, X ($X=1-([PhCOCl]_{org}/[PhCOCl]_{i,org})$) vs. time and the equilibrium conversion of PhCOCl, X_{eq} ($X_{eq}=1-([PhCOCl]_{eq,org}/[PhCOCl]_{i,org})$) vs. reaction factors were then investigated. $[PhCOCl]_{i,org}$ and $[PhCOCl]_{eq,org}$ are the initial concentration and the equilibrium concentration of PhCOCl in the organic phase, respectively.

From previous work[18] and our preliminary experiments, the reaction of PhCOCl and $RCOO^{-}$ ion catalyzed by PNO in the medium H_2O/CH_2Cl_2 produced the unsymmetric acid anhydride (PhCOOCOR) and the limiting reactant (PhCOCl) was consumed completely. These $RCOO^{-}$ ions included benzoate, formate, acetate, propanoate, 2-methylpropanoate, valerate, hexanoate, heptanoate, and octanoate ions. We found that only half the PhCOCl was consumed under similar reaction conditions if sodium butanoate (PrCOONa) was used as reactant in the aqueous phase. The equilibrium concentration of PhCOCl remained constant for 3 h and the expected product (PhCOOCOPr) was not observed. However, PhCOOH, PrCOCl and $(PhCO)_2O$ (trace) were observed. No butanoic acid anhydride ($(PrCO)_2O$) was detected. This peculiar phenomenon is distinct from reaction of PhCOCl with other $RCOO^{-}$ ions. This observation indicates that reaction of PhCOCl and $PrCOO^{-}$ ion catalyzed by PNO in the medium H_2O/CH_2Cl_2 is an equilibrium chemical system (Eq. R1).

Kinetics of the Reaction of Benzoyl Chloride and Butanoate Ion Catalyzed by PNO. (A) Effect of Butanoate Ion : The reaction proceeded at constant ionic strength (I=0.500 M, adjusted by $NaNO_3$). For $[PhCOCl]_{i,org}=0.0100$ M, $[PNO]_{i,aq}=6.00\times10^{-4}$ M, at 18 °C, the obtained equilibrium conversion of PhCOCl (X_{eq}) is 0.536 ± 0.003, 0.564 ± 0.008, and 0.552 ± 0.003 for $[PrCOO^{-}]_{i,aq}=0.500$, 0.300, and 0.100 M, respectively. This result indicates that X_{eq} was insensitive to the concentration of $PrCOO^{-}$ ion in the aqueous phase. Nevertheless, as shown in Fig. 1 (b, c), the initial rate of reaction increased with increasing concentration of $PrCOO^{-}$ ion before reaching the equilibrium state.

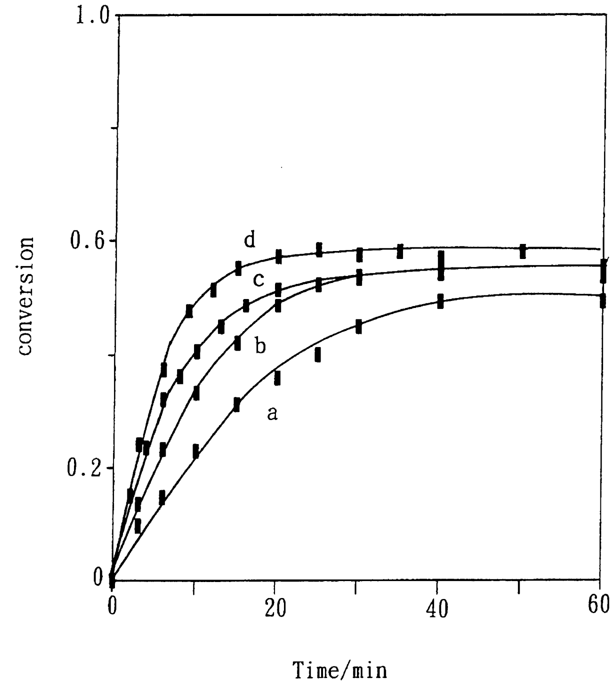


Fig. 1. Conversion of PhCOCl vs. time in the PNO-catalyzed two-phase PhCOCl–$PrCOO^{-}$ reaction; $[PhCOCl]_{i,org}=0.0100$ M, $[PNO]_{i,aq}$=(a): 2.00×10^{-4} M; (b,c,d): 6.00×10^{-4}M, ;T=(a,b,c): 18 °C; (d): 25 °C; $[PrCOO^{-}]_{i,aq}$=(a,c,d): 0.500 M; (b): 0.0100 M; pH=6.50.

(B) Effect of Pyridine 1-Oxide : As expected, the effect of PNO on the reaction is significant. The initial rate of reaction increased with increasing concentration of PNO. Typical conversion (X) vs. time are shown in Fig. 1 (a,c). The obtained initial rate of reaction (R_i) are 6.20×10^{-4}, 1.00×10^{-3}, and 1.35×10^{-3} M min^{-1} for $[PNO]_{i,aq}=2.00\times10^{-4}$, 4.00×10^{-4}, and 6.00×10^{-4} M, respectively. A good linear relation for R_i vs. $[PNO]_{i,q}$ was obtained. The reaction of PhCOCl and PNO in the organic phase is the rate-determining step. The corresponding values of X_{eq} are 0.494 ± 0.006, 0.519 ± 0.006, and 0.536 ± 0.003 for $[PNO]_{i,aq}=2.00\times10^{-4}$, 4.00×10^{-4}, and 6.00×10^{-4} M, respectively.

(C) Effect of benzoate Ion : The effect of $PhCOO^{-}$ ion on the reaction was tested by comparing the conversion after 10 min of reaction. As shown in Table 1, the reaction rate and the equilibrium conversion were enhanced with added PhCOONa. As PhCOCl partially reacted with $PhCOO^{-}$ ion to produce stable $(PhCO)_2O$, the equilibrium conversion of PhCOCl increases with the existence of $PhCOO^{-}$ ion.

(D) Effect of Chloride Ion : The effect of chloride ion the reaction was tested by adding benzyltriethylammonium chloride (BTEAC), soluble in CH_2Cl_2 in contrast to NaCl. For $[PNO]_{i,aq}=6.00\times10^{-4}$ M, $[PhCOCl]_{i,org}=0.0100$ M, at 18 °C, $[PrCOO^{-}]_{i,aq}$= (0.500—0.480 M), and I=0.500 M, the equilibrium con-

Table 1. Effect of PhCOONa Concentration on the Equilibrium Conversion of PhCOCl and the Yield of $(PhCO)_2O$ in the PNO-Catalyzed Two-Phase PhCOCl–$PrCOO^-$ Reaction System[a)]

$[PhCOO^-]_{aq}$/M	X_{eq}	$(PhCO)_2O$/%
0	0.494±0.006	2.78
0.00250	0.521±0.009	7.10
0.00500	0.560±0.010	9.60
0.0100	0.554±0.009	18.7
0.0200	0.554±0.006	25.7

a) $[PNO]_{i,aq}=2.00\times10^{-4}$ M, $[PrCOO^-]_{i,aq}=0.500$ M, $[PhCOCl]_{i,org}=0.0100$ M, pH=6.50, 18 °C. $X_{eq}=1-([PhCOCl]_{eq,org}/[PhCOCl]_{i,org})$.

version of PhCOCl altered insignificantly in the presence of BTEAC (0.0100 M or 0.0200 M). Nevertheless, the rate of reaction rate increased with BTEAC present because BTEAC is itself a NPTC catalyst capable of carrying $PrCOO^-$ ion to the organic phase for reaction according to Eq. R2.

$$PhCOCl_{(org)} + PrCOO^-_{(aq)} \xrightarrow{\text{BTEAC}} PhCOOCOPr_{(org)} + Cl^-_{(aq)} \quad \text{(R2)}$$

(E) Effect of pH : The effect of OH^- on the reaction was tested for $[PNO]_{i,aq}=6.00\times10^{-4}$ M, $[PhCOCl]_{i,org}=0.0100$ M, and $[PrCOO^-]_{i,aq}=0.0500$ M, at 25 °C. As shown in Fig. 2 (a,b,c), the equilibrium conversion (X_{eq}) was insignificantly affected by the variation of pH within the range of 6.5—10.7. However, it increased substantially with increasing pH for pH>11.4 (Fig. 2 (d,e)). At pH=12.7, the value of X_{eq} was equal to 1.0, i.e. PhCOCl being completely consumed (Fig. 2 (f)). The initial rate of reaction (R_i) increased also with increasing concentration of OH^- ion. For $[PNO]_{i,aq}=6.00\times10^{-4}$ M and $[PhCOCl]_{i,org}=0.0100$ M, at 18 °C, the values of k_{obs} are: 0.235 min^{-1} and 0.133 min^{-1} for $[NaOH]_{i,aq}=0.500$ M and $[MeCOONa]_{i,aq}=0.500$ M, respectively. For $[PhCOCl]_{i,org}=0.0100$ M, the values of k_h at 18 °C are 6.70×10^{-2} min^{-1} and 5.73×10^{-3} min^{-1} for $[NaOH]_{i,aq}=0.500$ M and $[MeCOONa]_{i,aq}=0.500$ M, respectively. The initial rate of reaction (R_i) vs. $[PNO]_{org}$ is presented in Table 2. Hydroxide ion exhibits both basic and nucleophilic effects. According to its basic effect, OH^- ion affects the distributions of RCOOH and PNO in the organic phase. According to its nucleophilic effect, OH^- ion competes effectively with $RCOO^-$ ion as a nucleophile to react with PhCOCl. For pH>11.4, the nucleophilic effect exceeded the basic effect, and R_i increased with increasing concentration of OH^- ion. For 8.7<ph<10.7, both effects of OH^- ion compensated each other, and R_i was unaffected by OH^- ion. For pH<6.5, the solution was weakly acidic and the contents of RCOOH and PNO in the organic phase increased. Therefore, the rate of reaction at pH<6.5 was greater than that at pH=8.7. In most kinetic experiments, the pH of the aqueous phase was kept about 6.5.

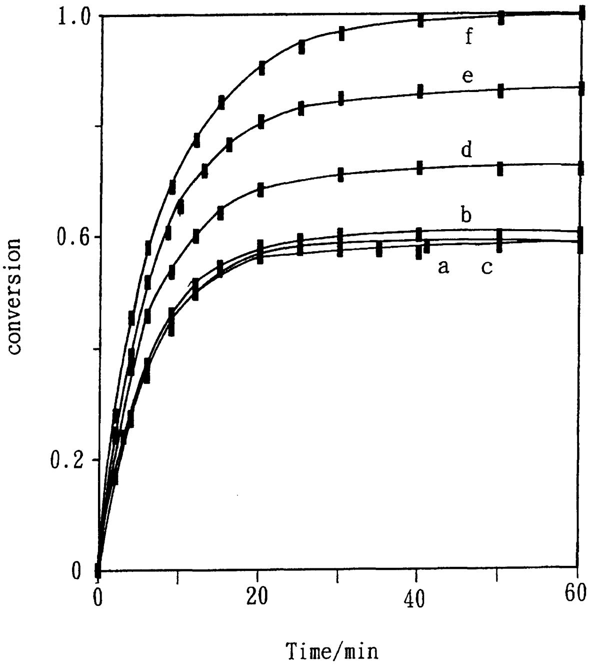


Fig. 2. Conversion of PhCOCl vs. time in the PNO-catalyzed two-phase PhCOCl–$PrCOO^-$ reaction; $[PhCOCl]_{i,org}=0.0100$ M, $[PNO]_{i,aq}=6.00\times10^{-4}$ M, $[PrCOO^-]_{i,aq}=0.500$ M, 25 °C, pH=(a): 6.50; (b): 8.70; (c): 10.7; (d): 11.4; (e): 12.0; (f): 12.7.

Table 2. Effect of the pH-Value on the Initial Rate of the PhCOCl–$PrCOO^-$ Reaction and the Distribution of PNO in the H_2O/CH_2Cl_2 Medium

pH	R_i[a)]/10^{-3} M min^{-1}	pH	$[PNO]_{org}$[b)]/10^{-5} M
6.50	1.35	5.30	7.70
8.70	1.04	6.46	4.83
10.7	1.02	8.86	4.50
11.4	1.83	10.5	4.50
12.0	2.10	12.0	4.55
12.7	3.00		

a) $[PhCOCl]_{i,org}=0.0100$ M, $[PrCOO^-]_{i,aq}=0.500$ M, $[PNO]_{i,aq}=6.00\times10^{-4}$ M, 25 °C. b) $[PNO]_{i,aq}=1.00\times10^{-3}$ M, $[PrCOO^-]_{i,aq}=0.500$ M, 18 °C.

(F) Effect of Temperature : As shown in Fig. 1 (b,d), the equilibrium conversion (X_{eq}) is insignificantly influenced by temperature. For $[PNO]_{i,aq}=6.00\times10^{-4}$ M, $[PrCOO^-]_{i,aq}=0.500$ M, and $[PhCOCl]_{i,org}=0.0100$ M, the values of X_{eq} are 0.554±0.005, 0.536±0.003, and 0.577±0.007 at 10, 18, and 25 °C, respectively. The corresponding values of X_{eq} for $[PhCOCl]_{i,aq}=0.0200$ M are 0.581±0.006, 0.526±0.005, and 0.579±0.003 at 10, 18, and 25 °C, respectively. This heterogeneous equilibrium phenomenon is obtained from the combination of various equilibrium reactions and is distinct from a single homogeneous reaction equilibrium. Therefore the temperature cannot directly reflect the equilibrium between reactants and products or intermediates.

Kinetics of the Reaction of Butanoyl Chloride

and Benzoate Ion Catalyzed by PNO. The reaction of PrCOCl and $PhCOO^-$ ion catalyzed by PNO in the medium H_2O/CH_2Cl_2 rapidly reached the equilibrium state of reaction (R1) and with no acid anhydride observed. Therefore, the relative reactivities of PhCOCl and PrCOCl are understood on comparing the time required to reach the equilibrium state. The equilibrium concentration of PhCOCl us relatively small in the PrCOCl–$PhCOO^-$ reaction system. Under similar conditions, the reactivity of PrCOCl is obviously much greater than that of PhCOCl.

(A) Effect of Pyridine 1-Oxide : As the reaction reached equilibrium quickly the effect of PNO on the rate of reaction was not obtained. However, PNO had a great effect on the equilibrium yield of PhCOCl. As shown in Table 3 and Fig. 3, the equilibrium concentration of PhCOCl increases with increasing concentration of PNO. A little PhCOCl was produced even in the absence of PNO. As PrCOCl is reactive, OH^- ion can compete effectively with PNO even at small concentration. When the pH was constant at 6.50, the PNO-catalyzed reaction of PrCOCl and $PhCOO^-$ ion was favored by PNO at a larger concentration. Therefore, the equilibrium concentration increased with increasing concentration of PNO. For example, the observed equilibrium concentration of PhCOCl was $(7.09\pm0.04)\times10^{-4}$ M for $[PrCOCl]_{i,org}=0.0100$ M, $[PhCOO^-]_{i,aq}=0.500$ M, $[PNO]_{i,aq}=4.00\times10^{-4}$, 18 °C, but it decreased to $(0.772\pm0.072)\times10^{-4}$ M in the presence of NaOH (0.04 M), which is almost equal to the value of $[PhCOCl]_{eq,org}$ obtained for the uncatalyzed reaction. As reported in the literature,[20] in the uncatalyzed reaction PhCOCl is produced via reaction (R3).

$$PrCOCl_{(org)} + PhCOOH_{(org)} \rightleftarrows PhCOCl_{(org)} + PrCOOH_{(org)} \quad (R3)$$

Table 3. Effect of PNO Concentration of the Equilibrium PhCOCl Concentration in the PNO-Catalyzed Two-Phase PrCOCl–$PhCOO^-$ Reaction System[a)]

$[PNO]_{i,aq}/10^{-4}$ M	$[PhCOCl]_{eq,org}/10^{-4}$ M
0.00	1.16±0.001 (0.854±0.064)[b)]
2.00	4.73±0.02
4.00	7.09±0.04 (0.772±0.072)[b)]
6.00	8.89±0.06 (16.7±0.1)[c)] (15.3±0.1)[d)]
8.00	10.3±0.1
10.3	11.5±0.1

a) $[PrCOCl]_{i,org}=0.0100$ M, $[PhCOO^-]_{i,aq}=0.500$ M. b) 0.04 M NaOH added. c) $[BTEAC]_{i,aq}=0.0100$ M, $[PhCOO^-]_{i,aq}=0.490$ M. d) $[BTEAC]_{i,aq}=5.00\times10^{-3}$ M, $[PhCOO^-]_{i,aq}=0.495$ M.

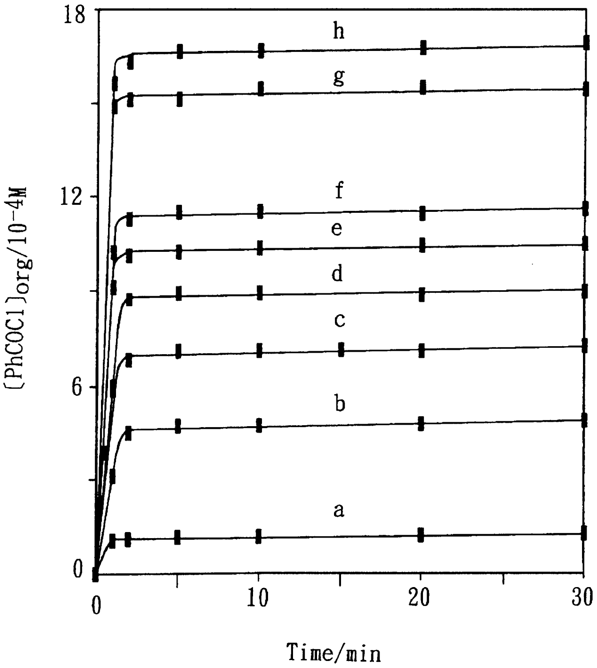


Fig. 3. Concentration of PhCOCl vs. time in the PNO-catalyzed two-phase PrCOCl–$PhCOO^-$ reaction; $[PrCOCl]_{i,org}=0.0100$ M, $[PhCOO^-]_{i,aq}=0.500$ M, 18 °C, [PNO]=(a): 0 M; (b): 2.00×10^{-4} M; (c): 4.00×10^{-4} M; (d,g,h): 6.00×10^{-4} M ; (e): 8.00×10^{-4} M; (f): 10.0×10^{-4}M;$[PhCOO^-]_{i,aq}$=(g)]:0.495M;(h): 0.490M;$[BTEAC]_{i,aq}$=(g)]:0.495=(g):5.00×10^{-3} M; (h): 0.0100 M; pH=7.5.

For $[PhCOCl]_{i,org}=1.00\times10^{-3}$ M, the values of the equilibrium constant (K) of reaction (R3) in CH_2Cl_2 are $(7.92\pm0.40)\times10^3$, $(8.53\pm0.79)\times10^3$, $(7.73\pm0.36)\times10^3$, and $(6.93\pm0.44)\times10^3$ for $[PrCOOH]_{i,aq}=0.500$, 0.750, 1.00, and 1.50 M, respectively. For $[PhCOCl]_{i,org}=1.00\times10^{-3}$ M, the values of K are $(8.03\pm0.52)\times10^3$, $(7.73\pm0.36)\times10^3$, $(7.58\pm0.57)\times10^3$, and $(6.23\pm0.60)\times10^3$ at 10, 18, 25, and 32 °C respectively. The thermodynamic parameters obtained from the plot of $\ln(K)$ vs. $1/T$ are $\Delta H^\circ=-(7.51\pm3.02)$ kJ mol^{-1}, $\Delta S^\circ=(48.5\pm10.3)$ J mol^{-1} K^{-1}. Hence that both ΔH° and ΔS° favor the forward reaction of (R3). This result is consistent with the fact that the reactivity of PrCOCl is greater than that of PhCOCl.

(B) Effect of Chloride Ion : Similarly, the effect of Cl^- ion on the reaction in the PrCOCl–$PhCOO^-$ reaction system was tested with BTEAC. As presented in Table 3 (b,c) and Fig. 3 (g,h), the equilibrium concentration of PhCOCl increased significantly in the presence of Cl^- ar a relatively small concentration, in contrast to the effect of Cl^- ion the PhCOCl–$PrCOO^-$ reaction system.

Mechanism of the Reaction

As proposed by a Mathias and Vaidya,[10] the reaction processes for PNO-catalyzed IPTC reaction of acyl chloride (RCOCl) with carboxylate ion ($R'COO^-$) in the medium $\mathrm{H_2O/CH_2Cl_2}$ can be summarized in reactions (R4) and (R5)

$$\mathrm{RCOCl + PNO \xrightarrow[CH_2Cl_2]{} RCOONP^+Cl^-} \tag{R4}$$

$$\mathrm{RCOONP^+ + R'COO^- \xrightarrow[H_2O]{} RCOOCOR' + PNO} \tag{R5}$$

The presumed intermediate, 1-(acyloxy)pyridinium chloride ($\mathrm{RCOONP^+Cl^-}$) formed in the organic phase can rapidly transfer to the aqueous phase for reaction with $\mathrm{R'COO^-}$ ion. Kuo and Jwo[18] investigated the kinetics and mechanism of the PNO-catalyzed reaction of PhCOCl with $\mathrm{PhCOO^-}$ ion in $\mathrm{H_2O/CH_2Cl_2}$ medium. Under appropriate conditions, they found that the reaction is essentially irreversible and that the rate of reaction was represented according to Eq. 1

$$-\frac{\mathrm{d[PhCOCl]_{org}}}{\mathrm{d}t} = (k_\mathrm{h} + k_\mathrm{c}[\mathrm{PNO}]_{\mathrm{i,aq}})[\mathrm{PhCOCl}]_\mathrm{org} = k_\mathrm{obs}[\mathrm{PhCOCl}]_\mathrm{org} \tag{1}$$

in which k_h is the uncatalyzed rate coefficient and k_c is the catalyzed rate coefficient and k_obs is the observed pseudo-first-order rate coefficient.

In contrast, the PNO-catalyzed IPTC reactions of the $\mathrm{PhCOCl\text{–}PrCOO^-}$ and $\mathrm{PrCOCl\text{–}PhCOO^-}$ systems lead to equilibrium as described by reaction (R1). Therefore, a distinct reaction scheme is required. Based on the above kinetic results, Scheme I is proposed for this reaction. The reactions can be classified as being in the organic or aqueous phases or at the interface.

Scheme I.

Organic-phase reactions :

$\mathrm{PhCOCl + PNO \rightleftharpoons PhCOONP^+ + Cl^-}$ (O1f, O1r)

$\mathrm{PrCOCl + PNO \rightleftharpoons PrCOONP^+ + Cl^-}$ (O2f, O2r)

$\mathrm{PrCOOCOPh + PNO \rightleftharpoons PrCOO^- + PhCOONP^+}$ (O3f, O3r)

$\mathrm{PrCOOCOPh + PNO \rightleftharpoons PhCOO^- + PrCOONP^+}$ (O4f, O4r)

$\mathrm{(PhCO)_2O + PNO \rightleftharpoons PhCOONP^+ + PhCOO^-}$ (O5f, O5r)

$\mathrm{(PrCO)_2O + PNO \rightleftharpoons PrCOONP^+ + PrCOO^-}$ (O6f, O6r)

$\mathrm{PrCOCl + PhCOOH \rightleftharpoons PhCOCl + PrCOOH}$ (O7f, O7r)

$\mathrm{PhCOOH + PNO \rightleftharpoons PNOH^+ + PhCOO^-}$ (O8f, O8r)

$\mathrm{PrCOOH + PNO \rightleftharpoons PNOH^+ + PrCOO^-}$ (O9f, O9r)

Interface reactions :

$\mathrm{PhCOONP^+_{(org)} + Cl^-_{(org)} \rightleftharpoons PhCOONP^+_{(aq)} + Cl^-_{(aq)}}$ (I1f, I1r)

$\mathrm{PhCOONP^+_{(org)} + Cl^-_{(org)} \rightleftharpoons PhCOONP^+_{(aq)} + Cl^-_{(aq)}}$ (I2f, I2r)

$\mathrm{PhCOOCOPr_{(org)} \rightleftharpoons PhCOOCOPr_{(aq)}}$ (I3f, I3r)

$\mathrm{(PhCO)_2O_{(org)} \rightleftharpoons (PhCO)_2O_{(aq)}}$ (I4f, I4r)

$\mathrm{(PrCO)_2O_{(org)} \rightleftharpoons (PrCO)_2O_{(aq)}}$ (I5f, I5r)

$\mathrm{PNO_{(org)} \rightleftharpoons PNO_{(aq)}}$ (I6f, I6r)

$\mathrm{PhCOOH_{(org)} \rightleftharpoons PhCOOH_{(aq)}}$ (I7f, I7r)

$\mathrm{PhCOOH_{(org)} \rightleftharpoons PhCOOH_{(aq)}}$ (I8f, I8r)

Aqueous-phase reactions :

$\mathrm{PhCOONP^+ + PrCOO^- \rightarrow PhCOOCOPr + PNO}$ (A1)

$\mathrm{PPrCOONP^+ + PhCOO^- \rightarrow PrCOOCOPh + PNO}$ (A2)

$\mathrm{PhCOONP^+ + PhCOO^- \rightarrow (PhCO)_2O + PNO}$ (A3)

$\mathrm{PrCOONP^+ + PrCOO^- \rightarrow (PrCO)_2O + PNO}$ (A4)

$\mathrm{PhCOONP^+ + H_2O \rightarrow PhCOOH + PNO + H^+}$ (A5)

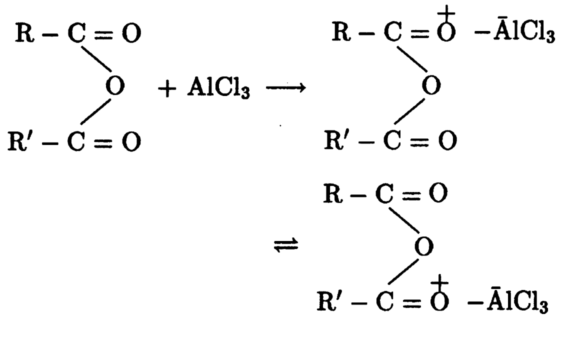
$\mathrm{PrCOONP^+ + H_2O \rightarrow PrCOOH + PNO + H^+}$ (A6)

$\mathrm{PhCOOH \rightleftharpoons PhCOO^- + H^+}$ (A7)

$\mathrm{PrCOOH \rightleftharpoons PrCOO^- + H^+}$ (A8)

f: forward reaction, r: reverse reaction.

The main reactions in the organic phase involve the reactions of PNO. For the $\mathrm{PhCOCl\text{–}PrCOO^-}$ reaction, the initial rate of reaction was a linear function of $[\mathrm{PNO}]_{\mathrm{i,aq}}$. This result indicated that the rate-determining step took place in the organic phase before reaching equilibrium (reaction (O1f) and (O2f)). At an early stage of the $\mathrm{PhCOCl\text{–}PrCOO^-}$ reaction, the main reaction was that of PhCOCl and PNO in the organic phase to produce the intermediate ($\mathrm{PhCOONP^+}$) which rapidly transferred to the aqueous phase to react with $\mathrm{PrCOO^-}$ to yield PhCOOCOPr (reaction (A2)) or with water to produce PhCOOH (reaction (A5)). The product PhCOOCOPr then transferred to the organic phase for further reaction. In the reaction of PhCOCl with $\mathrm{PhCOO^-}$ ion, a stable acid anhydride $\mathrm{(PhCO)_2O}$ was produced that did not participate significantly in further reactions. Therefore, an irreversible kinetic behavior of the reaction was observed, The limiting reactant (PhCOCl) was completely consumed and acid anhydride was obtained at a high yield. In contrast PhCOOCOPr was unstable and reacted with PNO to produce intermediate products ($\mathrm{PhCOONP^+}$ and $\mathrm{PrCOONP^+}$) according to reactions (O3f) and (O4f).[21] The behavior of the reaction of PhCOOCOPr and PNO is similar to that of the reaction of mixed carboxylic anhydride (RCOOCOR′) with $\mathrm{AlCl_3}$ used for the acylation of benzene.[22] The reaction of catalyst $\mathrm{AlCl_3}$ and RCOOCOR′ produced the intermediates in equilibrium with each other (reaction (R6)).



(R6)

Because of the dielectric property of CH_2Cl_2, the reaction of PhCOCl and PNO in CH_2Cl_2 is more reasonably expressed as reaction (R7).

$$\mathrm{PhCOCl + PNO \rightleftharpoons (PhCOONP^+Cl^-) \rightleftharpoons PhCOONP^+ + Cl^-} \quad \text{(R7)}$$

However, for convenience, reaction (R7) was simplified as reaction (O1). Some other reactions in the organic phase were simplified in the same way. The intermediates $PhCOONP^+Cl^-$ and $PrCOONP^+Cl^-$ are soluble in water and reactive. Therefore, a pseudo-steady state approximation was applied to the kinetics of the reaction. In this system, $PhCOONP^+$ (or $PrCOONP^+$) ion was consumed by reacting rapidly with $PhCOO^-$ (or $PrCOO^-$) ion to produce acid anhydride (reactions (O3r) or (O4r)). It also reacted with Cl^- ion to reproduce PhCOCl (reactions (O1r) or PrCOCl (reaction O2r)) or transferred to the aqueous phase for reaction. In the PhCOCl–$PrCOO^-$ reaction system, PrCOCl was produced because of the combined reactions (O4f) and (O2r). Similarly, PhCOCl was produced because of the combined reactions of (O3f) and (O1r).

The effect of Cl^- ion is explained by considering reactions (O1), (O2), (O3), (O4), (I1), and (I2). In the PrCOCl–$PhCOO^-$ reaction system, reaction (O1r) is enhanced on addition of chloride ion because of the relatively small concentration of PhCOCl. The increased equilibrium concentration of PhCOCl is more significant in the PrCOCl–$PrCOO^-$ reaction system. In contrast, the effect of chloride ion the PhCOCl–$PrCOO^-$ reaction system is less significant due to the relatively large equilibrium concentration of PhCOCl.

As shown in Figs. 1 and 3, the reactivity of PrCOCl was greater than that of PhCOCl. The rate coefficient of reaction (O2f) was expected exceeded that of (O1f). Similar results were obtained for homogenous reaction (O7). The equilibrium constant (K) of reaction (O7) is about 10^3—10^4. Reactions (O8) and (O9) are considered because the protonation of PNO by RCOOH affects the concentration of free PNO in the organic phase, which turn affects the reaction rate.

The interface reactions included the distribution of intermediate, acid anhydride, catalyst and carboxylic acid between two phases. The rates of mass transfer of those compounds were greater than those of the reactions taking place in both phases. Therefore, the overall reaction was not affected by mass transfer. However, the equilibrium state was built up with transfer of the catalyst or the product from one phase to another.

The intermediate also reacted with other species in the aqueous phase. For example, the intermediate $PhCOONP^+$ reacted with $PrCOO^-$ ion, $PhCOO^-$ ion H_2O to produce PhCOOCOPr, $(PhCO)_2O$, and PhCOOH via reactions (A1), (A3), and (A5), respectively. In the PhCOCl–$PrCOO^-$ reaction system, the yield of PhCOOH was about 30%. Only a trace amount of $(PhCO)_2O$ was obtained. As $(PhCO)_2O$ is very stable, it does not react further. Therefore, adding $PhCOO^-$ ion to the reaction system increased both the yield of $(PhCO)_2O$ and conversion of PhCOCl. In contrast, the PhCOOCOPr produced is highly reactive and reacts immediately with PNO. Therefore, PhCOOCOPr was not observed during reaction. Similarly, $PrCOONP^+$ ion reacted with $PhCOO^-$ ion, $PrCOO^-$ ion and H_2O to produce PrCOOCOPh, $(PrCO)_2O$, and PrCOOH via reactions (A2, A4, and A6) respectively. Some symmetric acid anhydrides with small alkyl such as $(PrCO)_2O$, $(EtCO)_2O$, and $(MeCO)_2O$ were unstable and decomposed rapidly in the presence of H_2O or alcohol.[23] Therefore, $(PrCO)_2O$ was not observed during the reaction.

Additional reaction steps (R8)—(R12) are considered to explain the effect that OH^- ion, which competes effectively with PNO to react with acyl chlorides and acid anhydrides when pH>11.

$$\mathrm{PhCOCl + 2OH^- \rightleftarrows PhCOO^- + Cl^- + H_2O} \quad \text{(R8)}$$

$$\mathrm{PrCOCl + 2OH^- \rightleftarrows PrCOO^- + Cl^- + H_2O} \quad \text{(R9)}$$

$$\mathrm{PrCOOCOPh + 2OH^- \rightleftarrows PrCOO^- + PhCOO^- + H_2O} \quad \text{(R10)}$$

$$\mathrm{(PhCO)_2O + 2OH^- \rightleftarrows 2PhCOO^- + H_2O} \quad \text{(R11)}$$

$$\mathrm{(PrCO)_2O + 2OH^- \rightleftarrows 2PrCOO^- + H_2O} \quad \text{(R12)}$$

Therefore, concentrations of all of PhCOCl, PrCOCl, intermediate, and use the unsymmetrical acid anhydride decreased in the presence of sufficient OH^- ion. The presence of OH^- ion exhibits the effects of increasing the rate of reaction and the equilibrium conversion of PhCOCl as observed in the PhCOCl–$PrCOO^-$ reaction system. When $[OH^-]_{i,aq}=0.500$ M, complete consumption of PhCOCl was observed and the catalysis of PNO was insignificiant. In the present work, the pH value was generally kept at about 6.5, at which reactions (R8)—(R12) are negligible.

It is generally believed that the exchange reaction of acyl halide (RCOX) and carboxylic acid (R′COOH) in a homogeneous organic medium takes place via a mixed anhydride intermediate (reaction (R13))

$$\mathrm{RCOX + R'COOH \rightleftharpoons (RCOOCOR' + HX) \rightleftharpoons RCOOH + R'COX} \quad \text{(R13)}$$

The establishment of the equilibrium of (R13) depends greatly on the reactivities of RCOX, R′COX, and RCOOCOR′. As reported by Ugi and Beck,[24] the relative reactivities of acyl chlorides (RCOCl) toward hydrolysis in 89% aqueous Me_2CO at −20 °C were R=Cl_3C (9200), Cl_2CH (2800), $ClCH_2$ (1.9), CH_3 (1.0), C_2H_5 (0.69), n-C_3H_7 (0.54), $(CH_3)_2CH$ (0.41), $(CH_3)_3C$ (0.068), n-C_5H_{11} (0.50), n-C_7H_{15} (0.43),

$PhCH_2$ (0.33), Ph_2CH (0.23), and Ph (0.0038). The reactivity of RCOCl is increased by electron-withdrawing substituent and lowered by either electron-donating or steric-hindered substituent. Acid anhydrides are less reactive than the corresponding acyl chlorides. However, similar electronic and steric effects are expected to be exhibited in acid anhydrides. As reported by Bunton et al.,[25)] the relative reactivities of acid anhydrides toward hydrolysis in dioxan/water (60/40 v/v) at 25 °C were $(MeCO)_2O$ (1.0)>MeCOOCOPh (0.74)>$(PhCO)_2O$ (0.033). Acid anhydrides with small alkyl groups are unstable and those with phenyl groups are relative stable. In the PNO-catalyzed two-phase reaction of PhCOCl with $RCOO^-$ ion (R=Ph, Me, Et, *i*-Pr, *n*-Bu, and *n*-C_5H_{11}), the expected acid anhydrides with yields higher than 90% could be obtained the limiting reactant PhCOCl was consumed completely. In contrast, the unexpected reversible exchange reaction was observed in the PNO-catalyzed two-phase reaction of PhCOCl with $PrCOO^-$ ion as shown in (R1). This observation cannot be explained simply by considering the reactivities of PhCOCl, PrCOCl, and PhCOOCOPr toward reacting with PNO alone. More complicated reactions as proposed in Scheme I are considered to be operating in establishing the reversible exchange reaction of (R1).

Conclusion

Two-phase equilibrium reaction was observed for IPTC reaction of PhCOCl and $PrCOO^-$ ion or of PrCOCl and $PhCOO^-$ ion catalyzed by PNO in the medium H_2O/CH_2Cl_2. The expected acid anhydride PhCOOCOPr was not observed. The rate-determining step takes place in the organic phase. PrCOCl is much more reactive than PhCOCl. In the PhCOCl–$PrCOO^-$ reaction system, the hydroxide ion enhanced both the initial rate of consumption and the equilibrium conversion of PhCOCl. The equilibrium conversion was affected insignificantly by Cl^- ion. In contrast, in the PrCOCl–$PhCOO^-$ reaction system, the equilibrium yield of PhCOCl increases with increasing concentration of Cl^- ion and decreases with increasing concentration of hydroxide ion. For both reaction systems, PNO increases the initial rate of reaction and the equilibrium conversion of acyl chloride.

We thank the National Science Council of the Republic of China (Grant No. NSC82-0402-E-007-302) for financial support.

References

1) C. M. Starks, *J. Am. Chem. Soc.*, **93**, 199 (1971).

2) C. M. Starks and C. Liotta, "Phase Transfer Catalysis, Principles and Techniques," Academic Press, New York (1978).

3) A. Branstrom, *Adv. Phys. Org. Chem.*, **15**, 267 (1977).

4) E. V. Dehmlow and S. S. Dehmlow, "Phase Transfer Catalysis," 2nd ed, Verlag Chemie, Weinheim (1983).

5) M. Makosza and M. Fedorynski, *Adv. Catal.*, **35**, 375 (1985).

6) H. H. Freedman, *Pure Appl. Chem.*, **58**, 857 (1986).

7) M. Ellwood, J. Griffiths, and P. Gregory, *J. Chem. Soc., Chem. Commun.*, **1980**, 181.

8) H. Iwamoto, T. Sonoda, and H. Kobayashi, *Tetrahedron Lett.*, **24**, 4703 (1983).

9) H. Kobayashi, T. Sonoda, and H. Iwamoto, *Chem. Lett.*, **1982**, 1185.

10) L. J. Mathias and R. A. Vaidya, *J. Am. Chem. Soc.*, **108**, 1093 (1986).

11) R. K. Smalley and H. Suschitzky, *J. Chem. Soc.*, **1964**, 755.

12) M. Yamada, Y. Watabe, T. Sakakibara, and R. J. Sudoh, *J. Chem. Soc., Chem. Commun.*, **1979**, 179.

13) W. K. Fife and Z. D. Zhang, *J. Org. Chem.*, **51**, 3744 (1986).

14) W. K. Fife and Z. D. Zhang, *Tetrahedron Lett.*, **27** **(41)**, 4933 (1986).

15) W. K. Fife and Z. D. Zhang, *Tetrahedron Lett.*, **27** **(41)**, 4937 (1986).

16) G. Hofe, W. Steglich, and H. Vorbruggen, *Angew Chem., Int. Ed. Engl.*, **17**, 569 (1978).

17) W. K. Fife and Y. Xin, *J. Am. Chem. Soc.*, **109**, 1278 (1987).

18) C. S. Kuo and J. J. Jwo, *J. Org. Chem.*, **57**, 1991 (1992).

19) Y. Hu, A. Harada, and S. Takahashi, *J. Mol. Catal.*, **60**, L13 (1990).

20) R. Adams and L. H. Ulich, *Pure Appl. Chem.*, **42**, 599 (1920).

21) D. S. Tarbell, *Acc. Chem. Res.*, **2**, 296 (1969).

22) W. R. Edwards and E. C. Sibille, *J. Org. Chem.*, **28**, 674 (1963).

23) M. Windholz, "Merck Index," 10th ed, Merck & Co., New York (1983), pp. 44, 7730, and 1562.

24) I. Ugi and F. Beck, *Chem. Ber.*, **94**, 1839 (1961).

25) C. A. Bunton, N. A. Fuller, S. G. Perry, and V. J. Shiner, *J. Chem. Soc.*, **1963**, 2918.